IMPACT OF STARTER FERTILIZERS ON OPTIMUM RATE, TIMING AND EFFICIENCY OF NITROGEN FERTILIZER FOR GRAIN SORGHUM IN TEXAS

A Thesis

by

SADIE ROSE CHURCH

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Ronnie W. Schnell
Committee Members,	Jake E. Mowrer
	J. Alex Thomasson
Head of Department,	David Baltensperger

August 2018

Major Subject: Agronomy

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ABSTRACT

Nitrogen (N) management is critical for producing high yielding grain sorghum in Texas. Many producers utilize planter options for starter fertilizer application, including in furrow or 2x2 placements of N and phosphorus (P). N and P applied as starter fertilizers could affect optimum rate, timing and nitrogen use efficiency (NUE) of N fertilizer in grain sorghum. Advances in technology for remote sensing enable rapid acquisition of crop canopy spectral measurements. Analysis of spatial variability of crop canopy reflectance may enable site-specific nitrogen (N) management in grain sorghum.

Two field studies were established in Burleson County, Texas during 2016 and 2017 to impose contrasting N status in grain sorghum. The first study employed a single side-dress application of increasing N fertilizer rates (0, 112,168,224, 280 kg ha^{-1}) for grain sorghum using three starter fertilizer applications. For the second study, timing (20, 42, 56, 65, 81 (2016) 32, 49, 66, 75, control (2017) days after planting) of side-dress N fertilizer application (168 kg N ha^{-1}) was evaluated for grain sorghum under three starter fertilizer applications. Starter fertilizer treatments (sub-plots) included ammonium polyphosphate (11-37-0) applied at 0, 56 (in-furrow) or 168 (2x2) L ha^{-1}. Spectral measurements (visible and NIR) of the sorghum canopy were made using ground-based at multiple dates during the growing season. Handheld sensors were also used to monitor N status throughout the season. Spectral indices and the handheld sensor values were used to evaluate and relate to crop biomass, grain yield and N content.

The optimal N rate in 2016 was 168 kg ha $^{-1}$, there was no significance across increasing rates in 2017. Starter fertilizers did not affect the increasing rates. The optimal timing of N in 2016 was <56 days after planting in 2016, in 2017 there was not a significant difference with delayed N application. Spectral measurements (visible and NIR) of the sorghum canopy were made using ground-based at multiple dates during the growing season. Handheld sensors were also used to monitor N status throughout the season. Spectral indices and the handheld sensor values were used to evaluate and relate to crop biomass, grain yield and N content.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Schnell, and my committee members, Dr. Mowrer, and Dr. Thomasson, for their guidance and support throughout the course of this research.

Thanks also go to research assistants Thavilla Silverio and Jonathan Moreno and student workers Jonah Hutchinson, Braydon Stockton, Colton Adams, Josh Corso, and David Bryant for their assistance in the field and lab.

Finally, thanks to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a thesis committee consisting of Professors Ronnie W. Schnell and Jake E. Mowrer of the Department of Soil and Crop Science and Professor J. Alex Thomasson of the Department of Biological and Agricultural Engineering.

All work for the thesis was completed by the student, under the advisement of Ronnie W. Schnell of the Department of Soil and Crop Sciences.

Funding Sources

This work was made possible in part by Texas Grain Sorghum Producers.

NOMENCLATURE

N	Nitrogen
P	Phosphorus
NUE	Nitrogen Use Efficiency
NIE	Nitrogen Internal Efficiency
ANE	Agronomic Nitrogen Efficiency
NRE	Nitrogen Recovery Efficiency
PFP	Partial Factor Productivity
PNU	Plant Nitrogen Uptake
NDVI	Normalized Difference Vegetative Index
NIM	Nitrate Ion Meter
SPAD	Soil-Plant Analyses Development
DAP	Days After Planting
a.i.	Active Ingredient
n.s.	Not Significant

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CHAPTER I

INTRODUCTION

Sorghum [Sorghum bicolor (L.) Moench] is a drought tolerant crop that is often grown under environmental conditions not suitable for many other crops (Moghaddam et al., 2007). Limited rainfall and dryland cropping systems provide opportunities for inclusion of grain sorghum in crop rotations in Texas. In 2017, Texas was the second largest producing state behind Kansas with 730, 000 thousand hectares of grain sorghum planted. In the United States, Kansas and Texas make up 75% of the total grain sorghum acres (USDA, 2017). Grain sorghum produced in Texas during 2016 was valued at $388 million (USDA, 2017). Sorghum producers must optimize crop inputs to maximize yield and economic return. There are many inputs in producing high yielding sorghum with fertilizer being the single greatest input cost for production in Texas (Johnson, 2017).

Nitrogen (N) is the most limiting nutrients in producing high yielding grain sorghum. N plays a role in biological and physiological functions in plants, specifically in photosynthetic processes and protein building (Leghari et al., 2016). Consequently, N application in crop production is required due to the removal of N in grain or biomass and supply and retention of N by soil. When there is not an adequate amount of N, sorghum leaves may turn yellow and in severe cases premature leaf loss may occur (Vanderlip, 1993). The kernel weight, kernel size, and number of kernels are determined by the amount of N in the plant (Mahama et al., 2014; Vanderlip, 1993; Whitney, 1998). A grain yield of 6.3 Mg ha^{-1} uses approximately 200 kg ha^{-1} of N (Whitney, 1998). Therefore, it is necessary to fertilize the crop according to yield potential. The quantity of N applied is just one component of N management.

There are many different application methods for nitrogen fertilizer. Common practices in Texas include subsurface injection, surface dribble, broadcast, and broadcast incorporate. Nitrogen fertilizer can be split-applied (application at planting and application midseason) or applied all at once. Studies have demonstrated that a single application can have negative environmental effects (Cassman et al., 2002; Khosla et al., 2000; Randall and Hoeft, 1988; Tilman et al., 2002). This is due to N being a mobile nutrient in soil and susceptible to leaching below the root zone and subsequently reaching surface or ground water (Khosla et al., 2000; Whitney, 1998). Consequently, it is important to apply N in a method to reduce loss and increase fertilizer use efficiency (Cassman et al., 2002; Tilman et al., 2002). Numerous management strategies have emerged to increase the fertilizer efficiency and reduce loss.

Application of small amounts of fertilizer with or near the seed at planting is known as starter fertilizer application. According to Randall et al. (1985) the main objective to starter fertilizers is to increase fertilizer use efficiency. Various planter attachments are used to conveniently apply fertilizer at planting, reducing field traffic and saving time. Planter attachments offer two common options for applying starter fertilizer, in furrow (also known as pop up) or 2x2 (5 cm to the side of the seed trench and 0-5cm in depth). The placement of starter fertilizer is crucial in preventing seedling injury and providing economic benefits to the farm (Randall and Hoeft, 1988). The maximum rate of the starter is dependent on placement due to stand loss caused by a salt injury when starter placement is close to the seed (Raun et al., 1986). Potential benefits to starter fertilizer are an increase of early season growth, higher grain yield, and increased nitrogen use efficiency (Bermudez and Mallarino, 2002).

Split N applications can increase N use efficiency (NUE) and grain yields (Stecker et al., 1993). Split N applications also help provide an adequate amount of nitrogen during the grain fill process in order to maximize yield. Growing point differentiation is when the plant initiates panicle development, about 30 days after emergence (Vanderlip, 1993). It is during this critical period that yield potential is established and when water or nutrient stress could reduce yield. Sorghum panicle initiation coincides with rapid nitrogen assimilation approximately 45 days after emergence. Most recommendations suggest having all N fertilizer applied by this time to maximize yield potential (Stichler et al., 1997). Starter fertilizer generally provides only a portion of crop N requirements, requiring subsequent N applications to meet total crop demand. How starter fertilizers influence optimum rate and timing of N fertilizer in sorghum is uncertain.

Determining the optimum N rate is essential for efficient N use in the plant and for proper plant development (Buah et al., 2012; Fageria and Baligar, 2005b; Mahama et al., 2014; Mahama et al., 2016; Maman et al., 2017). Studies have shown that increased N rates result in sorghum reaching flowering quicker (Mahama et al., 2014; Mahama et al., 2016). Sorghum height and biomass are also positively affected by increasing N application rates (Buah et al., 2012; Maman et al., 2017). Inadequate N application rate is detrimental to grain yield, resulting in reduced grain fill or small kernel size (Mahama et al., 2014). Current fertilization recommendations for grain sorghum in Texas are yield-based, with 2 kg of N for 100 kilograms per hectare of grain (Stichler et al., 1997). Excess N application can negatively affect soil and water quality and reduce NUE, meaning growers spend more than necessary to meet crop needs for N (Cassman et al., 2002).

In addition to simply N in starter fertilizers, applying N and phosphorus (P) fertilizer at planting could affect the optimum rate and timing of N side dress fertilizer. Previous studies have shown improved growth rate at the beginning of the season when N and P starter fertilizer is used instead of N only starter (Gordon and Whitney, 1995; Touchton and Karim, 1986).

Improved early season growth and vigor could impact yield potential and optimum N requirements. Moreover, early season nutrient demands of grain sorghum could be satisfied by starter fertilizer applications and potentially expand the optimum window for N side dress applications. N side dress timing should be further evaluated for fertilizer programs utilizing common starter fertilizer practices.

Optimizing N fertilizer programs for contrasting starter fertilizer practices is expected to contribute to greater NUE in grain sorghum. Improving NUE will provide environmental benefits for Texas and economic benefits for producers. Tilman et al. (2002) stated improving NUE in cereal grains can lead to higher yields and quality while reducing N losses. Cassman et al. (2002) discusses how applied N that is not taken up by the crop is prone to volatilization, denitrification, and leaching, which can lead to economic and agronomic farm losses and environmental hazards over time. Low NUE can decrease water quality, aquatic habitats, and increase purification costs for drinking water (Cassman et al., 2002; Tilman et al., 2002). This can help producers get a higher economic benefit from their fertilizer.

Many measurements and calculations have been used to describe NUE of grain crops and cropping systems (Fageria and Baligar, 2005a). NUE calculations are designed to provide estimates of output (kg of grain) per unit of input (kg of N). Calculations are commonly based on the difference method, where reference plots with no added N are compared to plots receiving N fertilizer. NUE and agronomic N efficiency (ANE) are synonymous (in most publications) and calculated as shown below. Additional terms used related to NUE include: partial factor productivity (PFP), nitrogen recovery efficiency (NRE), nitrogen internal efficiency (NIE) and plant N uptake (PNU);

$$\mathrm{ANE}=\frac{(\mathrm{Y_n}\text{-}\mathrm{Y_0})}{\mathrm{N_r}}$$

$$\mathrm{PFP}=\frac{\mathrm{Y_n}}{\mathrm{N_r}}$$

$$\mathrm{NRE}=\frac{(\mathrm{PNU_n}\text{- }\mathrm{PNU_0})}{\mathrm{N_r}}$$

$$\mathrm{NIE}=\frac{(\mathrm{Y_n}\text{-}\mathrm{Y_0})}{(\mathrm{PNU_n}\text{- }\mathrm{PNU_0})}$$

Where Y_n is grain yield (kg ha^{-1}) for plots receiving fertilizer N, Y_0 is grain yield (kg ha^{-1}) for plots without fertilizer N, N_r is the applied N fertilizer rate (kg ha^{-1} of N), PNU_n is plant N uptake (kg ha^{-1}) of N fertilized plot, PNU_0 is plant N uptake (kg ha^{-1}) of unfertilized plot. NUE measurements are essential for evaluation of contrasting fertilizer and N management practices. A wide range of NUE for contrasting rate, timing and placement of N in corn and other grain crops have been reported for some regions of the U.S. (Cassman et al., 2002; Fageria and Baligar, 2005a). NUE for corn has been reported between 19 and 42 (kg grain kg^{-1} N) depending on management practices evaluated (Attia et al., 2015; Ciampitti and Vyn, 2014; Jaynes, 2015; Kovács et al., 2015a). Information on NUE for sorghum is limited. Understanding how common fertilizer practices interact with N management to affect NUE is urgently needed for sorghum.

The availability of crop sensors, unmanned aerial systems (UAS), satellite imagery and data management systems is enabling farmers to collect and analyze spatial reflectance data that may be used to improve crop N management (Clay, 2011; Graeff and Claupein, 2003; Pierce and Nowak, 1999; Thorp et al., 2015; Zhang and Kovacs, 2012). The potential ability spectral sensors have to detect N stress and allow farmers to alter management of fertilizer inputs could further contribute to increases in NUE in grain sorghum (Graeff and Claupein, 2003; Singh et al., 2017; Zhao et al., 2005). Yet the ability of spectral sensors to detect N stress in sorghum and at developmental stages that enable corrective action is uncertain. Furthermore, deficiencies in total N supply to grain sorghum could be masked by early season fertilizer practices, including starter fertilizer practices.

Grain sorghum yield and crop development are affected by nutrient management practices. Minimal research has been done in Texas to measure the grain and biomass yield, and NUE for grain sorghum response to starter fertilizers and N management. This study serves to improve our understanding of three main objectives. 1) Measure and compare grain sorghum yield in response to nitrogen fertilizer rates for sorghum with contrasting starter fertilizer practices. Determine NUE for contrasting starter practices with increasing fertilizer rates. 2) Measure and compare grain sorghum yield in response to nitrogen fertilizer timing for sorghum with contrasting starter fertilizer practices. Determine NUE for contrasting starter practices with increasing delay of side-dress N fertilizer application. 3) Evaluate sorghum leaf and canopy level reflectance under contrasting starter fertilizer and N management practices. Relate leaf and canopy reflectance to stem nitrate-N concentration, whole plant tissue N concentration, crop biomass and grain yield.

CHAPTER II

STARTER FERTILIZERS AND OPTIMUM NITROGEN RATE IN GRAIN SORGHUM

Introduction

Starter fertilizer applications involve injecting small amounts of fertilizer with or near the seed at planting. While starter fertilizers are common practice in many crops and production regions, limited information is available for grain sorghum. There are many options for placement, rate, and nutrient combinations in starter fertilizers. Starter fertilizer applications generally apply small amounts of N and P and can affect crop development and grain yield potential (Bermudez and Mallarino, 2002; Gordon and Whitney, 1995; Reeves et al., 1990). Essentially, starter fertilizers that contain N result in split application of N fertilizer. Split application of N fertilizer can increase NUE compared to single applications (Bermudez and Mallarino, 2002; Gordon and Whitney, 1995; Niehues et al., 2004; Scharf, 1999; Soroka, 2016; Touchton and Karim, 1986). With the potential to alter NUE and grain sorghum yield potential, optimum N fertilizer rates may be affected by starter fertilizer practices.

Placement of the starter fertilizer can affect crop growth and yield (Randall and Hoeft, 1988). There are many different placement options, including in-furrow, 2x2 (5cm to the side of the seed and 0-5cm below the soil surface), and broadcasted (Randall et al., 1985). In-furrow placement can increase seedling growth due to increased availability of nutrients in close proximity to the seed (Niehues et al., 2004). However, placing too much fertilizer too close to the seed can cause negative effects, such as stand reduction and slower emergence, due to salt injury (Raun et al., 1986). Niehues et al. (2004) showed that 2x2 placement decreases the potential for fertilizer salt injury. Physical separation of fertilizer bands and seed reduces injury potential yet is readily available to seedlings to promote efficient uptake of nutrients and rapid growth. Reeves et al. (1990) found placement of the starter solutions in-furrow or 2x2 both increased grain sorghum growth during the beginning of the season. Yet, the rate of the starter fertilizer and associated N content can impact the seedling growth and the crop yield (Scharf, 1999).

The impact of N on sorghum growth and development is well documented. A study in Kansas showed increasing N rates applied by hand 10-14 days after emergence results in a shorter time to flowering (Mahama et al., 2016). Mahama et al. (2016) found there was an increase of 4-8 days to flowering when comparing 45 kg N ha $^{-1}$ applied to 90 kg N ha $^{-1}$ applied to the sorghum. Mahama et al. (2014) also showed a 3-5 day reduction to flowering in multiple hybrids with N applied compared to no N applied. This indicates the sorghum development rates are greater as rates of N fertilizer increase. In addition to earlier flowering, sorghum biomass and plant height are affected by N application rates (Buah et al., 2012; Mahama et al., 2014; Mahama et al., 2016; Maman et al., 2017). Maman et al. (2017) observed an increase in biomass by 31 percent with N applied compared to no N. In Kansas, Mahama et al. (2014) found an increase in plant height when 45 kg N ha^{-1} was added, but there was not a difference in plant height with more than 45 kg N ha^{-1}. Therefore, N found in starter fertilizers and potential adjustments to optimum N fertilizer rates could affect growth and development in sorghum.

In addition to growth and development, grain yield and associated yield components can be altered with increasing N application rates. Mahama et al. (2016) reported an increase of kernels per head, kernel weight, and yield when increasing N rates were applied. Buah et al. (2012) found in Uganda with N depleted soil there was a significant increase in yield up to 80 kg N ha^{-1}. A long term study in Kansas (Schlegel and Bond, 2016) showed that N alone can increase yields when 180 kg N ha $^{-1}$ is applied on a soil with high K content. Differences in optimum N rates for contrasting studies may reflect differences in yield potential due to variation of environmental conditions and management practices. Likewise, differences in yield potential due to starter fertilizers could influence optimum N fertilizer rates.

Grain sorghum yield and crop development are affected by nutrient management practices. Minimal research has been done in Texas to measure the grain and biomass yield, and NUE for grain sorghum response to starter fertilizers and N management. The objectives of this study was to measure grain sorghum yield in response to nitrogen fertilizer rates for sorghum with contrasting starter fertilizer practices. To relate grain sorghum yield to nitrogen fertilizer rates for three starter fertilizer practices (no starter fertilizer, popup and 2x2) using linear and nonlinear regression. Determine NUE for contrasting starter practices with increasing fertilizer rates.

Materials and Methods

A two-year study was conducted in Burleson County, TX at the Texas A&M AgriLife Research farm (30.543297, -96.435316) to evaluate the impact of starter fertilizer on optimum rate of N fertilizer in grain sorghum under non-irrigated conditions. The study site is predominately Weswood silty clay loam (fine-silty, mixed, superactive, thermic Udifluventic Haplustepts) and Ships clay (very-fine, mixed, active, thermic Chromic Hapluderts) under conventional tillage using raised beds. Corn was the previous crop both years.

The study was arranged in a split plot design with four replications each of five main plots and three subplot fertilizer treatments for grain sorghum production during 2016 and 2017. Five nitrogen rates (0, 112, 168, 224, 280 kg N ha^{-1}) were the main plot and three starter fertilizer practices (in furrow, 2x2, none) were the sub-plot. Grain sorghum was planted on April 6, 2016 and March 22, 2017, both years using Dekalb DKS 51-01. A four-row John Deere 1705 planter was used to seed 160,550 seeds ha^{-1} on 76.2 cm spacing. The treatments of the starter solutions were liquid ammonium polyphosphate (11-37-0) applied at 1) In-Furrow - 56 L ha $^{-1}$ applied in the seed furrow 2) 2x2 - 168 L ha $^{-1}$ placed 5 cm to the side of the seed trench and up to a 5cm in depth and 3) No Starter - check. Subplots were four rows wide and 20.1 (2016) and 30.5 (2017) m in length. N rate treatments were applied at pre-boot (2016 delayed due to wet weather) and 6-leaf stage (2017) using a Scotts Turf Builder Classic Drop Spreader to band granular N fertilizer between rows. Granular urea (46-0-0) was applied to obtain the total N rates of: 1) 112kg N ha $^{-1}$ 2) 168 kg N ha $^{-1}$ 3) 224 kg N ha^{-1} 4) 280 kg N ha^{-1} (adjusted for N applied through starter practice).

Pesticide management strategies followed Agrilife recommendations. In 2016 a pre-emergence application consisted of Roundup WeatherMax at 2.8 L ha $^{-1}$ (a.i. glyphosate 48.8%), Dual II Magnum at 1.4 L ha^{-1} (a.i. s-metachlor 82.4%), and AAtrex 4L at 2.8 L ha $^{-1}$ (a.i. atrazine 42.6%). Cultivation was used pre-boot to control weeds during 2016. During 2016, Prevathon at 1 L ha^{-1} (a.i. chlorantraniliprole 5%) was used to control head insects (*H. zea, S. frugiperda, Nola sorghiella, Nezera viridula, Oebalus pugnax*). In 2017 a pre-emergence application of Outlook at 1 L ha^{-1} (a.i. dimethenamid-P 63.9%) and Roundup WeatherMax at 2.8 L ha^{-1} (a.i. glyphosate 48.8%) was applied. Cultivation practices occurred during growth stage 3 to remove grass and broadleaf weeds growing in between the rows in 2017. An in-season application of AAtrex 4L at 3.5 L ha $^{-1}$ (a.i. atrazine 42.6%) and Rifle at .58 L ha $^{-1}$ (dicamba 48.2%) were also be applied at growth stage 4 to suppress broadleaf weeds. An application of Tombstone at 70 mL ha $^{-1}$ (a.i. cyfluthrin 24.74%) was applied for midge (*Stenodiplosis sorghicola*) control on May 31. An application of Prevathon at 1 L ha^{-1} (a.i. chlorantraniliprole 5%) and Silencer at 0.21 L ha^{-1} (a.i.

lambda-cyhalothrin 12.7%) insecticides were applied growth stage 7 (6/20/2017) for headworm and stinkbug control (*H. zea, S. frugiperda, Nola sorghiella, Nezera viridula, Oebalus pugnax*).

Grain yield, moisture, and test weight were measured from the center two rows of each plot using a John Deere 3300 plot combine with a Harvest Master (HM800) on-board weigh system. Grain yield was adjusted to 14% moisture. In 2016 there were skips, due to poor establishment caused by ponded water after planting. The skips were measured and deducted from plot lengths to correct actual combine harvested area. In addition, all plants from a 3 m section of the first row of each plot was harvested (cut at the soil level by hand), separated into grain and aboveground biomass to measure dry matter and nitrogen content. Panicle weight, grain weight, test weight, moisture, and seed size were measured to calculate grain yield. The grain was milled (2 mm) and submitted for measurement of total nitrogen content. Sorghum aboveground biomass was weighed, chopped in the field using a forage chopper (Case 700). A subsample was weighed and dried (65C) using a forced air oven for 36 hrs or until moisture loss is minimal. Dry matter and moisture content was used to calculate dry matter yield for aboveground biomass. Dried subsamples were ground using a Wiley Mill 4 (2mm) and sent to the laboratory for N analysis. The tissue and grain samples collected at hand harvest were submitted to the Texas A&M Forage, Soil, Water Laboratory (College Station, TX) to measure total nitrogen in biomass and grain samples. Total N (plant tissue and grain) was determined by high-temperature combustion (McGeehan and Naylor, 1988).

Soil samples were collected at the beginning of the growing seasons to determine soil concentration of nitrate-N and extractable nutrients. Soil cores were collected using a GSRPS Giddings Machine Company soil probe. Soil was sampled 60 cm in depth and divided into 15 cm segments. The samples were sent to the Texas A&M Forage, Soil, Water Testing Laboratory for analysis. Mechlich III was used to extract phosphorus, potassium, calcium, magnesium, sodium, and sulfur and concentration measured by inductively coupled plasma (ICP) and atomic emission spectroscopy (Mehlich, 1984). A hydrogen selective electrode was used to determine soil pH in a 1:2, soil: deionized water extract. A conductivity probe was used to find soil electrical conductivity with the same soil: deionized water ratio as the soil pH (Schofield and Taylor, 1955). Nitrate nitrogen was extracted from the soil with 1 N KCL solution(Keeney and Nelson, 1982).

NUE was calculated five ways: agronomic N efficiency (ANE), partial factor productivity (PFP), N recovery efficiency (NRE), N internal efficiency (NIE) and plant N uptake (PNU).

$$\mathrm{ANE} = \frac{(\mathrm{Y_n} - \mathrm{Y_0})}{\mathrm{N_r}}$$

$$\mathrm{PFP} = \frac{\mathrm{Y_n}}{\mathrm{N_r}}$$

$$\mathrm{NRE} = \frac{(\mathrm{PNU_n} - \mathrm{PNU_0})}{\mathrm{N_r}}$$

$$\mathrm{NIE} = \frac{(\mathrm{Y_n}\text{-}\mathrm{Y_0})}{(\mathrm{PNU_n}\text{-}\mathrm{PNU_0})}$$

PNU =biomass N uptake + grain N uptake

Where Y_n is grain yield (kg ha^{-1}) for plots receiving fertilizer N, Y_0 is grain yield (kg ha^{-1}) for plots without fertilizer N, N_r is the applied N fertilizer rate (kg ha^{-1} of N), PNU_n is plant N uptake (kg ha^{-1}) of N fertilized plot, PNU_0 is plant N uptake (kg ha^{-1}) of unfertilized plot.

Statistical analyses was performed using SAS 9.4 (Cary, NC). The PROC GLM procedure was used to analyze variables of grain yield, NUE, biomass yield, grain and biomass

N as a split-plot design with fertilizer rate as the main plot and starter fertilizer as the subplot with years analyzed independently. When appropriate, means were compared using Fisher's L.S.D.

Results and Discussion

Soil Analysis

In both years of the study the mean P levels were optimum, which indicates a response to P fertilization may or may not occur (Table 1). Potassium (K), Calcium (Ca), and Magnesium (Mg) was optimum or above optimum. NO_3-N in 2016 was higher in the top 15cm than 2017. In 2017 10.3 ppm of NO_3-N was found in the top 0-60cm.

Table 1 Soil Analysis from the Top 15cm

Year	pH	Conductivity Umhos cm^{-1}	NO_3-N ppm	P ppm	K ppm	Ca ppm	Mg ppm	S ppm	Na ppm
2016	8	230	8.9	51	245	5672	210	11	23
2017	8	369	4	52	209	4999	178	9	8

Grain and Biomass Yield

Analysis of grain yield revealed that main effects of N rate and starter practices were significant in one year of the two-year study. Nitrogen fertilizer rate contributed significantly to ($p < 0.01$) increase in grain yield during 2016. In 2016, mean grain yields ranged from 5,156 to 6,258 kg ha^{-1} with increasing rates of N fertilizer applied (Figure 1). Application rates of 168 to 280 kg N ha^{-1} were associated with an increase in grain yield as much as 21% compared to 0 kg N ha^{-1}. Grain yield did not increase above the application rate of 168 kg N ha^{-1} during 2016. In 2017, grain yields were greater than 2016, however, there was not a significant difference in grain yield due to N application rate (Figure 1). Mean grain yield ranged from 7,671 to 8,042 kg ha^{-1} during 2017.

Despite lack of grain yield response during 2017, 2016 results were similar to other reports for grain sorghum response to N fertilizer. In Kansas, Schlegel and Bond (2016) found N applications up to 180 kg N ha^{-1} were associated with increased yields. Mahama et al. (2016), found an optimum N rate of 90 kg N ha^{-1} in a fallow cropping system gave the best economic returns. Grain yields, where no N fertilizer was applied, were 5,156 and 7,671 kg ha^{-1} in 2016 and 2017 in the current study. Previous studies found much lower levels of grain production when no N fertilizer was applied (Mahama et al., 2014; Mahama et al., 2016; Maman et al., 2017). This suggests that antecedent soil nitrogen contributed significantly to grain yield.

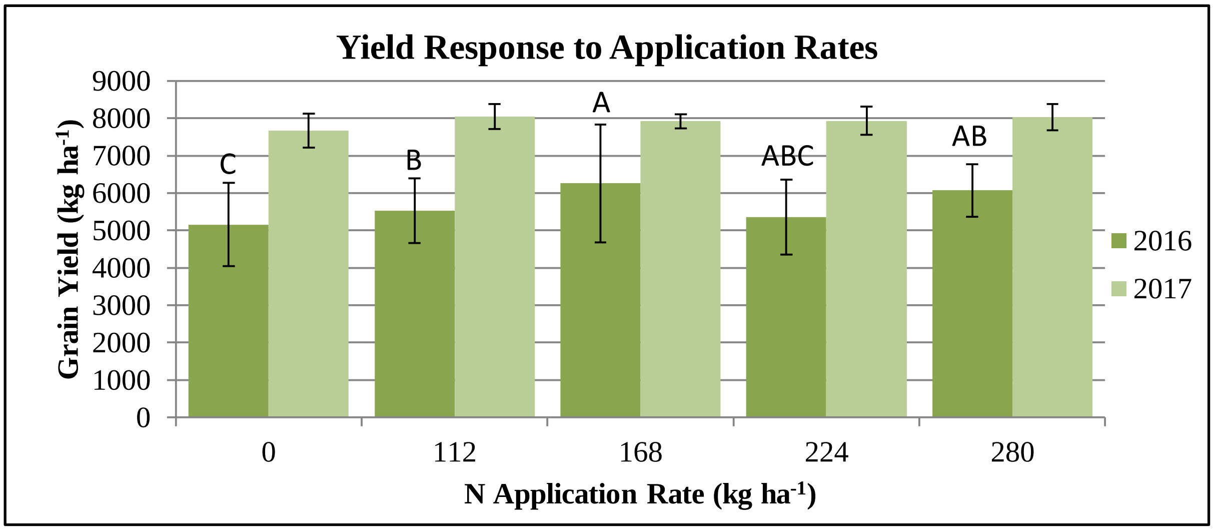


Figure 1 Yield Response to Application Rates. Average grain yield response to increasing N rates in 2016 and 2017. The different letters indicate significant differences with in N rates at $P < 0.05$. Error bars represent one standard deviation.

Antecedent soil nitrogen comprises residual soil nitrate-N and mineralization of organic N during the growing season. Residual soil nitrate-N averaged 19 kg ha $^{-1}$ in the top 15 cm (2016), 8 kg ha $^{-1}$ in the top 15 cm (2017) and 46 kg ha $^{-1}$ in the top 0-60 cm (2017). Crop residue from previous corn crops may have contributed to plant available N pools during the subsequent crop year (Blanco-Canqui and Lal, 2009; Dolan et al., 2006; Mullen et al., 2010; Salinas-Garcia et al., 2001). Mullen et al. (2010), found N content of 0.69% in corn cobs and 0.79% N content in corn stover when looking at potential removal of residues for biooil and biochar production. Salinas-Garcia et al. (2001), found the potential mineralizable N to be 4 kg ha $^{-1}$ day^{-1} from corn residue in a conventional tilled system in Mexico. In a corn stover removal study, Blanco-Canqui and Lal (2009) , found a 25-26% decrease in total soil N to a depth of 10 cm when they removed all stover, but the decrease was soil specific with silty loams texture class.

Previous year corn yields ranged from 11,300 kg ha^{-1} to 12,550 kg ha $^{-1}$ at the current study site. Higher N fertilizer rates used to obtain greater corn yields can result in greater organic carbon and N returned to soil (Liebig et al., 2002). Burgess et al. (2002) found that 70 to 80% of N in corn residues was released over a 2-year period under field conditions in Canada. It is likely the previous year's corn residue provided a source of mineralizable N in the current grain sorghum study.

Variation in grain yield was observed for contrasting starter fertilizer practices in 2016. Starter fertilizer practice did not affect ($p>0.05$) grain yields in 2017. Grain yield ranged from 5,000 to 6,000 kg ha^{-1}in 2016 and from 7,900 to 8,000 kg ha^{-1} in 2017 (Figure 2). In 2016, applying starter fertilizer as a 2x2 increased grain yield by 12.52% compared to the in-furrow and 14.2% compared to treatments with no starter fertilizer applied. In-furrow starter fertilizer application did not increase grain yield compared to treatments without starter fertilizer. While 2x2 starter fertilizer applications did increase grain yield, it also provides greater amounts of N and P compared to in-furrow applications. Scharf (1999) found comparable results in a corn N management system with the largest increase in yield being 1632 kg ha^{-1} with a 2x2 starter of 11-44-44 compared to a no starter treatment.

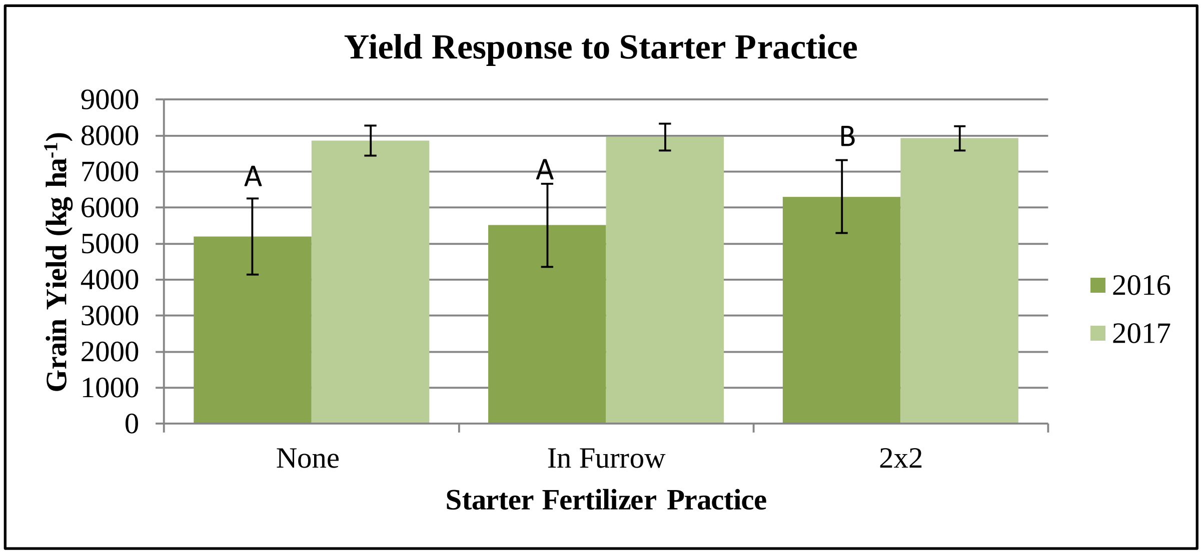


Figure 2 Yield Response to Starter Practice. Average grain yield response to starter practices in 2016 and 2017. The different letters indicate significant differences with in starter practices at $P < 0.05$. Error bars represent one standard deviation.

Biomass production was not affected by N treatments in either year. Despite differences in grain yield in 2016 there was no effect on biomass yield. The average biomass yield in 2016 and 2017 was 8,130 kg ha $^{-1}$ and 10,532 kg ha $^{-1}$. Powell and Hons (1992) found contrary results, where there was an increase in biomass production up to 112 kg N ha $^{-1}$ applied in their treatments. There was a positive significant increase in biomass with 224 kg N ha^{-1} applied in two of the four years with a conventional grain sorghum cultivar (ATx623 x RTx430) and intermediate type sorghum cultivars (ATx423 x RIO, ATx423 x HEGARI). Hons et al. (1986) found an increase in sorghum biomass production with increase N rates in a study comparing genotype response to N. All 3 genotypes (high energy sorghum, intermediate type sorghum, grain sorghum) responded positively to application rates up to the highest rate of 168 kg N ha^{-1}.

Plant Nitrogen Concentration and Uptake

Grain and aboveground biomass was sampled and analyzed separately for N concentration where mass of N in each treatment was determined. Grain N concentration and total N uptake was affected by N rate in both years (table 1). Grain N concentration ranged from 12.1 to 15.7 g kg^{-1} in 2016 and 11.2 to 13.3 g kg^{-1} in 2017. Increasing N fertilizer rates increased grain N concentration ($p<0.003$) 22% in 2016 and 16% in 2017 comparing the control N rate to the highest N rate. Total N uptake by grain ranged from 57.4 to 88.4 kg ha^{-1} in 2016 and 74.4 to 93.1 in 2017. Starter fertilizer practice did not affect N content of grain in either year and resulted in some variation in total N uptake by grain in one of two years. Hons et al. (1986) found similar results where the N concentration and PNU increased with the increasing N applications.

Aboveground biomass (excluding grain) N concentration was also affected by N fertilizer rates. Increasing N fertilizer rates increased biomass N concentration in 2016 and 2017 (Table 2). Aboveground biomass tissue N concentration ranged from 7.2 to 10.0 g kg^{-1}. Biomass N concentration was increased 25% comparing 0 to 280 kg N ha^{-1} in 2017. Hons et al. (1986) found a larger increase of N concentration when comparing 0 to 84 kg N ha^{-1} and 168 kg N ha^{-1} with a 24-75% increase. However, total N uptake in aboveground biomass was not affected by N rate in either year. Variation in aboveground biomass yield likely overshadowed variation in biomass N concertation due to N rates. Starter fertilizer practices resulted in variation in biomass N concentration in 1 of 2 years and did not affect total N uptake.

Total plant N uptake (PNU) was affected by increasing N rates in 1 of the 2 years. PNU was significantly ($p<.05$) increased, in 2016, with N rates up to 224 kg N ha^{-1}. There was a 43.6 kg N ha $^{-1}$ increase from the control (no N applied pooled across starter treatments) and the 224 kg N ha^{-1} rate. Similar PNU was reported by Ciampitti and Prasad (2016) with mean PNU of 138 kg N ha^{-1} from years 1965 - 2014 over 13 studies. The review paper found the studies conducted for 2001-2014 had lower mean PNU values of 60-80 kg N ha^{-1}.

Table 2 Plant Nitrogen Concentration and Nitrogen Uptake with Contrasting Application Rates. Average N concentration and N uptake of starter practices and increasing N rates for grain and biomass in 2016 and 2017. L.S.D. was used to compare means.

	N Concentration (g kg^{-1})		**N Uptake (kg ha^{-1})**		
	Biomass	Grain	Biomass	Grain	PNU
Starter			**2016**		
None	9.3	14.4	76.4	80.0	156.4
In-Furrow	8.4	14.0	69.8	67.7	137.5
2x2	9.4	14.1	74.6	76.9	151.5
Pr > F	0.022	n.s.	n.s.	0.012	n.s.
N-Rate					
0	8.1	12.1	60.1	57.4	117.5
112	8.5	13.4	76.1	70.7	146.8
168	9.2	14.6	76.0	81.8	157.8
224	9.5	14.8	85.0	76.1	161.1
280	10.0	15.7	70.7	88.4	159.1
Pr > F	0.003	<0.0001	n.s.	<0.0001	0.0095
Starter			**2017**		
None	8.4	12.4	88.6	84.8	169.5
In-Furrow	8.8	12.8	88.6	88.6	175.1
2x2	8.8	12.9	98.5	88.2	182.4
Pr > F	n.s.	n.s.	n.s.	n.s.	n.s.
N-Rate					
0	7.2	11.2	71.4	74.4	140.5
112	8.7	12.9	88.4	90.1	175.5
168	8.8	13.1	95.7	90.2	179.0
224	9.2	13.0	106.4	90.1	197.3

280	9.6	13.3	98.1	93.1	190.4
Pr > F	0.0005	<0.0001	n.s.	0.0005	n.s.
	n.s. = not significant (>0.05), PNU (total plant N uptake)				

Nitrogen Use Efficiency

Mean Partial factor productivity (PFP) was 33.1 kg kg^{-1} in 2016 and 46.1 kg kg^{-1} in 2017 (Table 2). Mean PFP was affected by N rate in both years of the study and was affected by starter fertilizer in one of two years. Mean PFP declined ($p < 0.0001$) 25 and 34% with N rates increasing from 112 to 168 kg N ha^{-1} in 2016 and 2017. Abunyewa et al. (2017) found similar results for PFP in sorghum, with a 23% decrease in PFP when N rates increased from 100 to 150 kg N ha^{-1}. In 2016, there was an interaction between starter practices and N rates for PFP (Figure 3). Mean PFP increased ($p < 0.05$) for in-furrow and 2x2 compared to grain sorghum

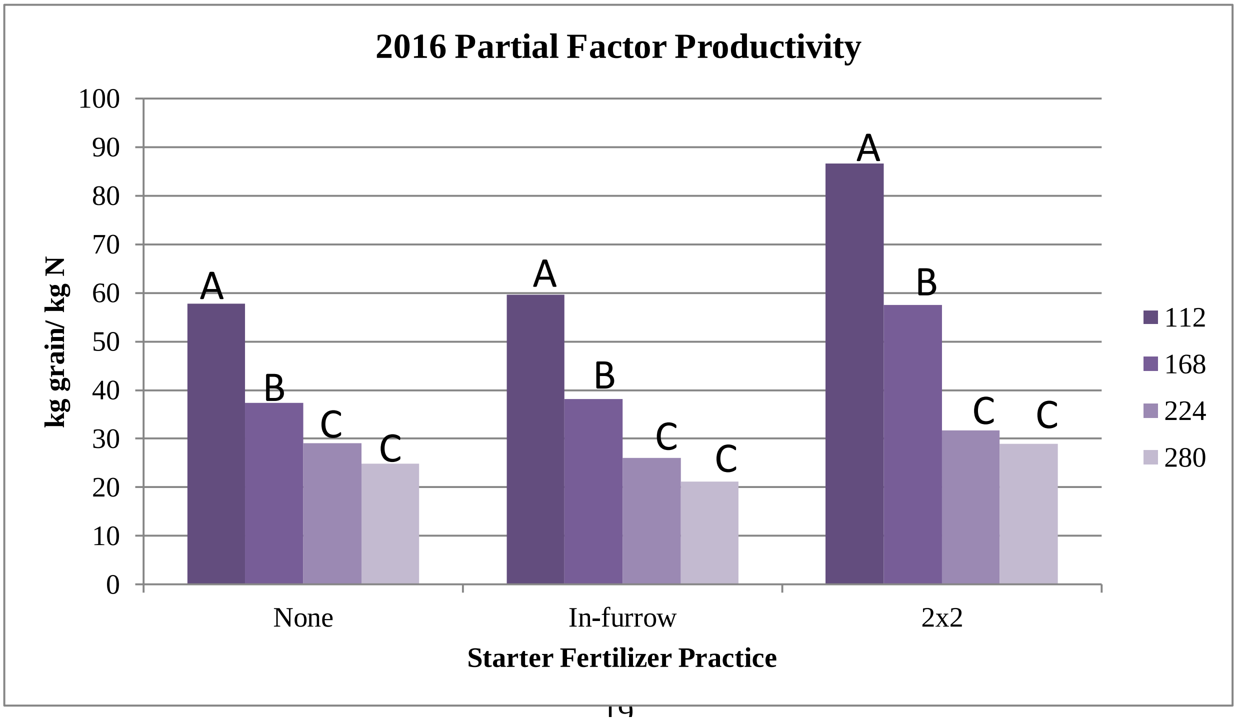


Figure 3 2016 Partial Factor Productivity. Average PFP of starter practices and increasing N rates in 2016. The different letters indicate significant differences of N rates with in each starter practice at $P < 0.05$. Legend units are kg N ha^{-1}.

without starter fertilizer applied.

Mean NRE ranged from 18.1 to 26.4% across all years and fertilizer treatments (Table 3). NRE did not differ among starter practices and N fertilizer rates in 2016 or 2017. The NRE mean values were lower than when compared to other studies. In a N management study with corn Kovács et al. (2015b) found higher NRE values of 43-81% recovery. In two of the three years of the study 90 kg N ha^{-1} had the highest NRE and it decreased with increasing rates up to 202 kg N ha^{-1} (Kovács et al., 2015b). Gagnon and Ziadi (2010) conducted a corn N management study comparing three different N sources (urea ammonium nitrate [UAN], calcium ammonium nitrate[CAN], aqua ammonia [AA]) and found a wide range NRE values from 19-75% recovery. UAN had the highest recovery of 75% with 100 kg N ha^{-1} as the N application rate. While, AA had the lowest NRE at 19% with a N rate of 200 kg ha^{-1}.

Mean nitrogen internal efficiency (NIE) ranged from 10.8 to 53.2 kg kg^{-1} across both years and all fertilizer treatments (Table 2). Mean NIE did not differ among starter practices or N rates in either year, although NIE was greater in 2016 compared to 2017. Ciampitti and Prasad (2016) found similar mean NIE (42 kg kg^{-1}) in high yielding sorghum (>8000 kg ha^{-1}). Moreover, considerable variability was observed in NIE (8-83 kg kg^{-1}), similar to the current study.

There was no difference in ANE in regards to starter or increasing rates over the two years. The mean ANE values ranged from 2.74 – 7.78 in 2016 and 2.37-16.21in 2017 across starters and N rates. A two year N rate study on grain sorghum in Nebraska found a decrease in ANE with increasing N rates from 50-150 kg N ha^{-1} applied (Abunyewa et al., 2017).

Table 3 Nitrogen Use Efficiency with Contrasting Application Rates. Average NUE values of starter practices and increasing N rates for grain and biomass in 2016 and 2017. L.S.D. was used to compare means.

	ANE	NRE	NIE	PFP
	kg kg^{-1}	%	kg kg^{-1}	kg kg^{-1}
Starter	**2016**			
None	3.72	18.3	32.6	30.49
In-Furrow	4.29	21.4	39.2	32.10
2x2	5.35	40.4	43.9	36.56
Pr > F	n.s.	n.s.	n.s	0.0202
N-Rate				
112	3.69	37.9	46.3	49.34
168	7.78	29.8	27.9	37.25
224	2.74	22.4	27.0	23.91
280	3.51	16.7	53.2	21.69
Pr > F	n.s.	n.s.	n.s	<0.0001
Starter	**2017**			
None	16.21	23.16	13.18	46.51
In-Furrow	2.73	35.84	16.17	46.14
2x2	2.37	29.99	11.42	45.69
Pr > F	n.s.	n.s.	n.s.	n.s.
N-Rate				
112	10.18	46.35	18.21	71.81
168	7.11	26.37	11.50	47.16
224	4.60	26.79	12.97	35.42
280	3.98	18.14	10.81	28.69
Pr > F	n.s.	n.s.	n.s.	<0.0001
	n.s. = not significant (>0.05),			

Conclusions

There has been minimal research on how starter fertilizer practices affect grain sorghum yield, optimum N rates and NUE in Texas. There are many advantages to split applying N in grain sorghum; to increase NUE, reduce environmental concerns, and increase yield (Buah et al., 2012; Mahama et al., 2014; Mahama et al., 2016;Tilman et al., 2002.). In the current study, the agronomic optimum N rate for grain sorghum was 168 kg N ha^{-1} in 2016 and less than 112 kg N ha^{-1} in 2017. While 2x2 application of starter fertilizer did increase grain yield in one year of the two-year study, yield enhancement was inconsistent. Furthermore, starter fertilizer practices did not affect optimum N rates and did not consistently improve NUE in grain sorghum.

While the lack of yield response and inability to improve NUE with starter fertilizers in the current study may bring into question the value of these practices, other factors may have contributed to the lack of response. The soil tests at the beginning of both years showed P was sufficient. This could have impacted the N+P starters negatively because the sorghum crop would not need to assimilate any more P causing economic and environmental loss. A N only starter would have been more appropriate. High grain yield and high levels of PNU in plots with no N applied suggests significant residual soil N was present, reducing uptake and use efficiency of N fertilizer. Mineralization of corn residues from previous crops at the study site likely contributed to addition plant available N in soil, reducing uptake of fertilizer N. The combination of these factors likely limited the ability to evaluate the full impact of starter fertilizers on grain sorghum yield and NUE.

CHAPTER III

STARTER FERTILIZERS AND NITROGEN FERTILIZER TIMING IN GRAIN SORGHUM

Introduction

Appropriate timing of N fertilizer applications can increase grain yield, NUE, and decrease environmental N loss (Bermudez and Mallarino, 2002; Cassman et al., 2002; Randall et al., 1985; Shrestha et al., 2010; Zotarelli et al., 2015). Split application of N fertilizer can increase NUE compared to single applications (Bermudez and Mallarino, 2002; Gordon and Whitney, 1995; Niehues et al., 2004; Scharf, 1999; Soroka, 2016; Touchton and Karim, 1986). Starter fertilizer applications involve injecting small amounts of N and P fertilizer with or near the seed at planting. For starter fertilizer containing N, the application essentially results in split application of N fertilizer. Application of some portion of N fertilizer with starter fertilizer could influence optimum timing for side-dress N application to grain sorghum. The potential to expand the optimum window for side-dress N application could ease logistical concerns for producers and potentially improve grain yield and NUE in sorghum.

Texas A&M AgriLife Extension recommends to apply all N fertilizer before panicle initiation and subsequent rapid plant growth to maximize grain yield potential (Stichler et al., 1997). Starter fertilizer N applications could be used to meet early season N demands and later side-dress N applications to correspond with rapid growth phases of grain sorghum. While information for split application of N in grain sorghum is limited, many studies have evaluated the impact of split N applications in corn. Miller (2012) demonstrated similar grain yield when N fertilizer was applied at V7 and V15 (leaf stage) when both received started fertilizer. However, Walsh et al. (2012) found applying N once midseason in corn will not compensate for early season N stress with yields reduced up to 15%. For corn, starter fertilizer appears to provide sufficient N for early season growth and enable later side-dress applications of N without yield loss. It is uncertain if this strategy will work in grain sorghum.

Grain sorghum yield and NUE are likely affected by timing of N fertilizer application. Starter fertilizers are commonly used in grain sorghum yet little information on the timing of split N applications is available and how it affects yield components, biomass, and NUE. The objective of this study is to measure grain sorghum yield in response to nitrogen fertilizer timing for sorghum with contrasting starter fertilizer practices (no starter, popup and 2x2). In addition, NUE will be determined for contrasting starter practices with increasing delay of side-dress N fertilizer application.

Methods and Materials

A two-year study was conducted at the Texas A&M AgriLife Research farm (30.543297, -96.435316) in Burleson County, TX to evaluate the impact of starter fertilizer on optimum timing of N fertilizer. The study site is predominately Weswood silty clay loam and Ships clay under conventional tillage using raised beds.

A split-plot design was used with 4 replications and 15 fertilizer treatments. N application timing (four or five dates) was the main plot and starter fertilizer (three practices) was the sub-plot. Planting dates of grain sorghum were April 6, 2016 and March 22, 2017, using Dekalb hybrid DKS 51-01. 160,550 seeds ha^{-1} on 76.2 cm spacing using a four-row John Deere 1705 planter. The treatments of the starter solutions were liquid ammonium polyphosphate (11-37-0) applied at 1) 56 L ha $^{-1}$ applied in furrow 2) 168 L ha $^{-1}$ placed 5 cm to the side of the seed trench and up to a 5cm in depth and 3) no starter fertilizer control. Subplots were four rows wide and 20.1 m long in 2016 and 30.5 m in length in 2017. Side-dress N fertilizer timing treatments were applied using a Scotts Turf Builder Classic Drop Spreader to broadcast granular urea (46-0-0) at a rate of 168 kg N ha^{-1} (less N applied through starter practice) between rows. Side-dress N was applied at approximately the 3-leaf, 6-leaf, 10-leaf, boot, and bloom growth stages. Application dates are reported as days after planting.

Pesticide management strategies followed Agrilife recommendations. In 2016 a pre-plant burn down consisted of a.i. glyphosate 48.8% (Roundup WeatherMax 2.8 L ha $^{-1}$), a.i. s-metachlor 82.4% (Dual II Magnum 1.4 L ha^{-1}), and a.i. atrazine 42.6% (AAtrex 4L 2.8 L ha $^{-1}$). Cultivation practices were used early in the season to control weeds. In growth stage 7, a.i. chlorantraniliprole 5% (Prevathon 1 L ha^{-1}) was used to control head insects (*H. zea, S. frugiperda, Nola sorghiella, Nezera viridula, Oebalus pugnax*). In 2017 a pre-plant burndown of a.i. dimethenamid-P 63.9% (Outlook 1 L ha^{-1}) and a.i. glyphosate 48.8% (Roundup WeatherMax 2.8 L ha^{-1}) was applied before planting. Cultivation practices occurred during growth stage 3 to remove weeds growing in between the rows in 2017. An in season application of a.i. atrazine 42.6% (AAtrex 4L3.5 L ha $^{-1}$) and a.i. dicamba 48.2% (Rifle 0.58 L ha $^{-1}$) were also applied at growth stage 4 to suppress broadleaf weeds. An a.i. cyfluthrin 24.74% insecticide (Tombstone 70 mL ha $^{-1}$) was applied to diminish any midge (*Stenodiplosis sorghicola*) infestation during growth stage 6. An application of a.i. chlorantraniliprole 5% (Prevathon 1 L ha^{-1}) and a.i. lambda-cyhalothrin 12.7% (Silencer 0.21 L ha^{-1}) insecticides were applied during growth stage 7 to remove any head insects (*H. zea, S. frugiperda, Nola sorghiella, Nezera viridula, Oebalus pugnax*) present.

A John Deere 3300 plot combine with a Harvest Master (HM800) on-board weigh system measured grain yield, moisture, and test weight from the center two rows of each plot. Grain yield was adjusted to 14% moisture. In 2016 there was poor establishment due to weather. If skips were present they were measured and removed from plot lengths to correct actual harvested area. All plants from a 3 m section of the first row of each plot was harvested by hand at the soil surface. It was separated into grain and biomass to measure dry matter and nitrogen content. Yield components (panicle weight, grain weight, test weight, moisture, and seed size) were measured to calculate grain yield. The grain was milled (2 mm) with a Wiley Mill 4 and submitted for measurement of total nitrogen content. Sorghum aboveground biomass was weighed, chopped in the field using a forage chopper (Case 700), and subsample weighed and dried (65C) using a forced air oven for 36 hours or until moisture loss was minimal. The dry matter yield for the biomass was calculated using the Dry matter and moisture. Dried subsamples were ground using a Wiley Mill 4 (2mm) and sent to the laboratory for tissue N analysis. The tissue and grain samples collected at hand harvest were submitted to the Texas A&M Soil, Water, Forage Laboratory to measure total N. Total N (plant tissue and grain) was determined by high-temperature combustion (McGeehan and Naylor, 1988).

Soil cores were taken using a GSRPS Giddings Machine Company soil probe at the beginning of the growing seasons to determine soil concentration of nitrate-N and extractable nutrients. Soil was sampled 60 cm in depth and divided into 15 cm segments. The samples were sent to the Texas A&M Soil, Water, Forage Testing Laboratory for analysis. Mechlich III was used to extract phosphorus, potassium, calcium, magnesium, sodium, and sulfur and concentration measured by inductively coupled plasma (ICP) (Mehlich, 1984). Soil pH was found using a hydrogen selective electrode in a 1:2, soil: deionized water extract. Soil electrical conductivity was determined using a conductivity probe with the same soil: deionized water ratio as the soil pH (Schofield and Taylor, 1955). Nitrate nitrogen was extracted from the soil with 1 N KCL solution(Keeney and Nelson, 1982).

Statistical analyses were performed using SAS 9.4 (Cary, NC). The PROC GLM procedure was used to analyze variable of grain yield, NUE, biomass yield, grain and biomass N as a split-plot design with fertilizer timing as the main plot and starter fertilizer as the subplot. When applicable, means were separated using L.S.D. linear and nonlinear regression to identify optimum side dress timing of N fertilizer.

Results and Discussion

Grain and Biomass Yield

Variation in grain yield response to N fertilizer application timing was significant ($p < 0.05$) in 2016 and was not significant in 2017. In 2016, grain yield was not reduced when N was applied within 56 days of planting (Figure 4A). However, no interaction ($p > 0.05$) between starter fertilizer practices and N fertilizer timing was observed. Despite starter fertilizers having no impact on N timing, yield loss was not observed when N fertilizer was applied beyond panicle initiation (~30 days after planting). Miller (2012) found similar results in corn where N fertilizer was applied up to V15 (~55 days after planting) without a decrease in yield. Grain yield was not affected by N application timing in 2017 (Figure 4B).

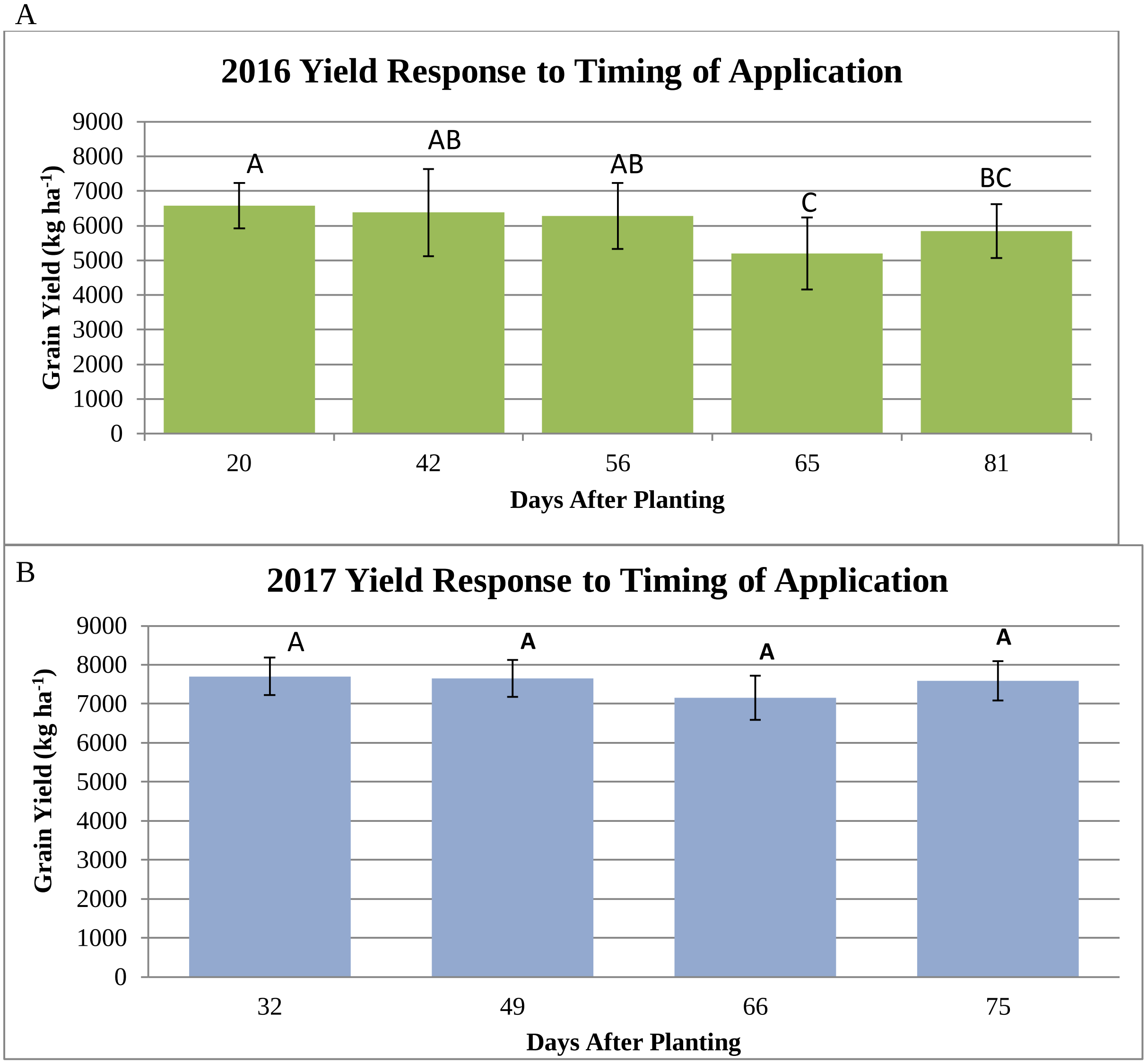


Figure 4 A) 2016 Yield Response to Timing of Application B) 2017 Timing Response to Timing of Application. A and B show the average grain yield response to the application of N side dress timing in 2016 and 2017. The different letters indicate significant difference. Error bars represent one standard deviation.

While starter fertilizer practices did not affect N fertilizer timing, starter fertilizer did affect ($P < 0.007$) grain yield in 2017 (figure 5). Starter fertilizer application as 2x2 and in-furrow increased yield by 413 to 415 kg ha^{-1} compared to grain sorghum without starter fertilizer. Walsh et al. (2012) found corn yield increased 15% when N was split applied instead of being applied only midseason.

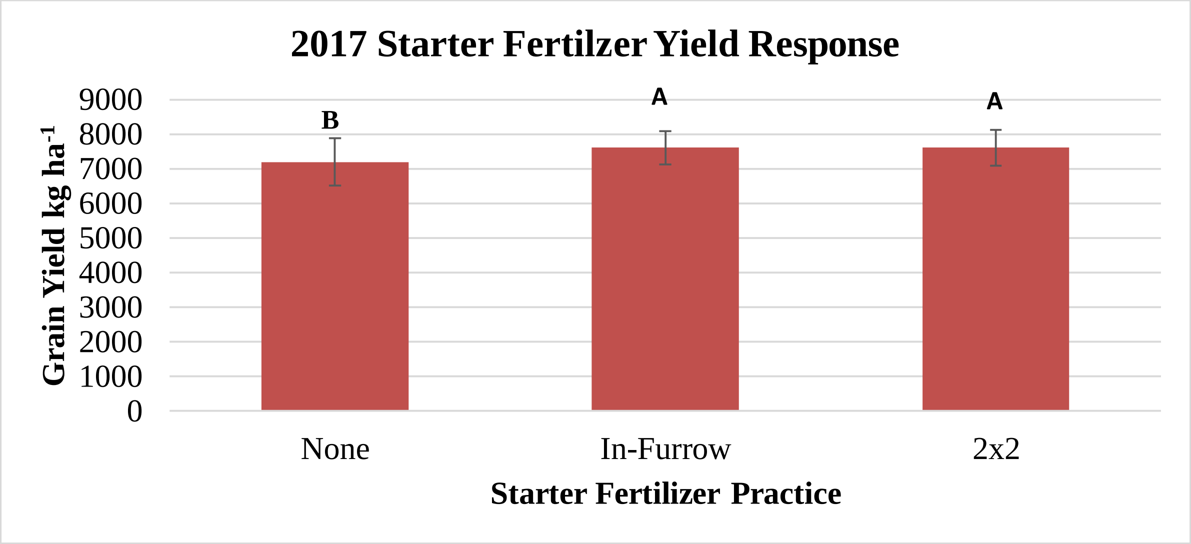


Figure 5 2017 Starter Fertilizer Yield Response. Average yield response to starter fertilizer practices. Different letters indicate significant differences in starter fertilizer practices at $P < 0.05$. Error bars represent one standard deviation.

Biomass production between treatments was not significant in 2016 or 2017. The mean in 2016 was 7,950 kg ha^{-1} and in 2017 the mean was 8,171 kg ha^{-1}. In contrast, Torbert et al. (2001) found with an increase of N applications (0-168 kg N ha^{-1}) in two of the three year study, when there was adequate rainfall, there was increase in biomass production and N uptake under three tillage systems (no-till, chisel no-beds, and chisel with beds). In a sweet sorghum N management trial (Almodares and Darany, 2006) found the best timing of application to be between the 3-8 leaf stages for highest biomass production compared to applying N at boot or soft dough stage.

The lack of response to the timing of application could have been due to sufficient levels of N and P in the soil. Residual soil nitrate nitrogen averaged 19 kg ha $^{-1}$ in the top 15 cm in 2016. In 2017, there was an average of 8 kg ha $^{-1}$ in the top 15 cm and 46 kg ha $^{-1}$ in the top 60 cm. This could have caused the sorghum to have adequate levels of N and P when the starter was applied. Both years of the study followed a high yielding corn crop. Nitrogen could have been added into the system through mineralization of the corn residue. Aulakh et al. (1991) found in a laboratory study that corn residues added 27 mg kg^{-1} of N to the soil. In a field study in Canada, Burgess et al. (2002) found 70-80% of N in corn residue was released into the soil over two years. In the current study there was no affect on the timing of the N application out to 75 days after planting in 2017, this could be due to the effect of mineralization of organic N from the corn residue adequately supplying the sorghum. Therefore, the application of 168 kg N ha^{-1} may have not been assimilated into the sorghum.

Plant Nitrogen Concentration and Uptake

Sorghum biomass N concertation was not affect by fertilizer timing in 2016 or 2017 and starter fertilizer practices affected ($p<0.05$) sorghum biomass N concentration in 2017 only (Table 4). Mean biomass N concentration was 0.99% in 2016 and 1.27% in 2017. Starter fertilizers increased sorghum biomass N concentration 8.2% compared to sorghum without starter fertilizer in 2017. Similar to sorghum biomass, grain N concentration was not affected by N fertilizer timing or starter practice in either year.

Nitrogen fertilizer application timing and starter practices did not result in significant variation in sorghum biomass in 2016 or 2017 and differences in grain yield in 2016 only. Therefore, uptake of N by sorghum biomass was not affected by N fertilizer timing of starter fertilizer practices in either year. In contrast, as N fertilizer timing was delayed in 2016, N uptake by grain decreased. There was a 20% decrease in grain N uptake when N fertilizer was applied at 65 days after planting compared to 42 days after planting. The impact of N fertilizer timing was negligible on grain N uptake in 2017. As a result of variation in biomass production, grain yield and N concentration in plant tissues, total plant N uptake was not affected by N timing in 2016 or

Table 4 Plant Nitrogen Concentration and Nitrogen Uptake with Delayed Nitrogen Application. Average N concentration and N uptake of starter practices and N application timings for grain and biomass in 2016 and 2017. L.S.D was used to compare means.

	N Concentration (g kg^{-1})		**N Uptake (kg ha^{-1})**		
	Biomass	Grain	Biomass	Grain	PNU
Starter			**2016**		
None	9.9	15.5	80.6	80.3	160.9
In-Furrow	9.6	15.7	73.7	77.2	150.8
2x2	10.1	15.2	77.8	83.1	160.9
Pr > F	n.s.	n.s.	n.s.	n.s.	n.s.
N-Timing					
20	9.4	15.0	72.7	84.6	157.3
42	10.3	15.9	79.5	86.6	166.0
56	9.9	15.7	79.7	84.3	164.0
65	9.6	15.5	70.2	68.8	139.0
81	10.3	15.4	84.7	76.8	161.6
Pr > F	n.s.	n.s.	n.s.	0.0044	n.s.
Starter			**2017**		
None	8.5	12.6	86.8	77.0	170.1
In-Furrow	9.2	12.8	110.6	82.8	205.5
2x2	9.3	12.8	113.6	82.6	206.2
Pr > F	0.005	n.s.	n.s.	0.017	0.041
N-Timing					
32	8.6	12.6	110.5	84.8	195.3

49	8.8	12.9	88.5	85.6	174.1
66	9.0	13.0	140.1	80.7	220.8
75	9.7	12.4	103.8	81.8	185.6
Pr > F	n.s.	n.s.	n.s.	n.s.	n.s.
	n.s. = not significant (>0.05), PNU (total plant N uptake)				

2017. Starter fertilizers did increase PNU by 20% in 2017 compared to sorghum without starter fertilizer.

While N fertilizer timing had no impact in sorghum N concentration and N uptake, starter fertilizers practice did influence N concentration and uptake in 2017. Starter fertilizer essential result in split application of N and did improve PNU compared to sorghum without starter fertilizer. Similar results were found for corn where PNU was increased when N was split applied compared to single applications (Niaz et al., 2014). The lack of sorghum response to N timing may have been influenced by residual soil N and mineralization of previous crop residues. Delayed N application would be expected to impact grain and biomass yield when N is limiting.

Nitrogen Use Efficiency

Nitrogen use efficiency in response to N fertilizer timing and starter fertilizers were evaluated during 2017. Timing of N application had no effect (P >0.05) on NUE (Table 5). However, starter fertilizer practices did increase (p<0.05) NRE compared to sorghum without starter fertilizer. There was greater than 2-fold increase in NRE for sorghum with in-furrow or 2x2 starter applications compared to sorghum without starter. While NRE was improved with starter fertilizer applications, and likely associated with split N applications, NRE was lower than reports for other crops with split applied N (Kovács et al., 2015a)

Duan et al. (2014) found greater ANE values when N and P was applied compared to N alone in a long-term (1995-2001) fertilizer management study for a wheat and corn rotation. When P was applied with N, ANE increased for wheat from 1 to 19 kg kg^{-1} (kg grain per kg nitrogen) and from 2 to 19 kg kg^{-1} for corn. In our study, we did not observe a difference in ANE due to starter applications, which provide N and P. However, our field was not limiting in soil test P and likely limited the impact of P applications. As previously stated, starter applications do provide an opportunity to split apply N which did result in greater NRE during 2017.

Table 5 Nitrogen Use Efficiency with Nitrogen Application Timing. Average NUE values of starter practices and N application timings for grain and biomass in 2017. L.S.D. was used to compare means.

	ANE	**NRE**	**NIE**	**PFP**
	kg kg^{-1}	%	kg kg^{-1}	kg kg^{-1}
Starter	**2017**			
None	3.10	18.74	7.07	43.44
In-Furrow	5.23	39.79	21.07	45.57
2x2	5.01	40.21	8.56	45.35
Pr > F	n.s.	0.0407	n.s.	n.s.
N-Rate				
32	5.52	33.7	16.88	45.86
49	5.20	21.10	30.28	45.53
66	2.25	48.89	-2.25	42.58
75	4.84	27.96	4.05	45.17
Pr > F	n.s.	n.s.	n.s.	n.s.
	n.s. = not significant (>0.05), PNU (total plant N uptake)			
	Agronomic Nitrogen Efficiency (ANE) $= \frac{Yn - Yo}{applied\ N\ rate}$	Nitrogen Recovery Efficiency (NRE) $= \frac{PNUn - PNUo}{applied\ N\ rate}\ x\ 100$	Nitrogen Internal Effciency (NIE) $= \frac{Yn - Yo}{PNUn - PNUo}$	Partial Factor Productivity (PFP) $= \frac{yield}{applied\ N\ rate}$

Conclusions

Application of a starter fertilizer with N could affect optimum timing for side-dress N application to grain sorghum. Possibly expanding the window of the side-dress N application could minimize concerns for producers who cannot get into the field early in the season. The timing of side dress N application is crucial in grain sorghum to have high yields, improved NUE, and is important for environmental factors (Bermudez and Mallarino, 2002; Cassman et al., 2002; Randall et al., 1985; Shrestha et al., 2010; Zotarelli et al., 2015). In the current study, starter fertilizers did not have an effect on the timing of side dress N in either year of the study. In 2016, N fertilizer could be applied up to 56 days after planting before the grain yield was impacted negatively. In 2017, the timing of the side dress did not affect grain yield, which could have been due to other factors.

For sorghum without N fertilizer 2017, high PNU and substantial grain yield was observed. This indicates there were high levels of plant available N in soil. Soil tests taken before planting indicated sufficient levels of P and significant levels of residual N, which exceeded the amount of N and P in the starter fertilizers. This likely contributed to the lack of response to starter fertilizer and the insignificant impact on the side-dress N timing. Moreover, uptake of N plots without N fertilizer exceeded the N found in the soil test. This indicates additional sources of N were found within the system. The study site used in both years followed high yielding corn, ranging from 11,300 kg ha^{-1} to 12,550 kg ha $^{-1}$. Mineralization of corn residue supplied additional plant available N throughout the growing season. With significant levels of residual soil N and mineralizable N, the ability to detect differences among starter fertilizers and their impact on timing of side-dress N in the grain sorghum was diminished.

CHAPTER IV

EVALUATION OF CONTRASTING SENSING TECHNOLOGY TO DETECT NITROGEN STRESS IN GRAIN SORGHUM

Introduction

Efficient monitoring of nitrogen status in grain sorghum can lead to improved N fertilizer management. (Graeff and Claupein, 2003; Singh et al., 2017; Wang et al., 2017; Zhao et al., 2005). A variety of sensors are commercially available that enable plant or canopy level measurements of field crops at increasing scales (Zhou et al., 2016). Nitrate selective electrodes have been used successfully to monitor nitrogen status of individual plants from petiole sap extruded from a variety of crops (Hartz et al., 1993; Hochmuth, 1994; Krusekopf et al., 2002). Similarly, hand held sensors have been used to estimate leaf chlorophyll content from reflectance readings at points on individual leaves (Bullock and Anderson, 1998). Additional developments in technology have enabled canopy level reflectance measurements of many crops using ground based proximal sensing. Recently, advancements in remote sensing technology has enabled field level measurement of crop canopy reflectance using unmanned aerial vehicles (UAV) or satellite systems. While technology has advanced and is readily available to producers, limited information is available for use of this technology to monitor and manage N in grain sorghum.

Many studies have successfully monitored N status in a variety of crops using leaf or canopy level reflectance measurements (Graeff and Claupein, 2003; Zhao et al., 2005). Many spectral bands and algorithms derived from a variety of spectral bands have been proposed to accurately monitor various canopy characteristics. Graeff and Claupein (2003) showed that N deficiency in corn plants can be correlated with leaf reflectance values in the near- infrared band

(750- 1350nm). Zhao et al. (2005) reported correlation between leaf N status and chlorophyll content to leaf reflectance near 550 nm and 710 nm for N deficient sorghum. Singh et al. (2017) found increasing leaf reflectance values in the green and red bands with increasing N fertilizer rates in sweet sorghum.

Of the numerous spectral bands and algorithms that have been developed to measure N status in crops, normalized difference vegetative index (NDVI) is one of the most frequently used vegetative indices to monitor crop canopies (Foster et al., 2017; Wang et al., 2017). Canopy level NDVI has been correlated with crop biomass, grain yield and N status (Foster et al., 2017; Lai-gang et al., 2011; Ma et al., 1996; Rambo et al., 2010b; Wang et al., 2016). Lai-gang et al. (2011) was able to correlate leaf N content from wheat with NDVI derived from a SPOT-5 satellite image. Ma et al. (1996) found NDVI (obtained from CropScan) to detect increasing N rates (0, 100, and 200 kg N ha^{-1}) throughout the growing season in a corn N management study. Wang et al. (2016) calculated NDVI from Landsat 5 TM images over a 10-year period and found a strong correlation between NDVI and corn grain yield at pre-silking. Indicating the crop stress is related to grain yield, whether it is due to N deficiency or environmental factors. Moreover, field level NDVI readily available to producers through many commercial providers of remote sensing data. NDVI is calculated as:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}$$

NDVI values range between -1 and 1 with green vegetation being positive values. Wang et al. (2017) measured seasonal variation of NDVI for wheat canopies and correlated N leaf status with NDVI at three growth stages (jointing, boot, and anthesis). In addition, NDVI was found to be highly correlated N status of biomass sorghum (Foster et al., 2017). This suggests that monitoring N status in grain sorghum using proximal or remote sensing platforms may be possible.

Handheld multispectral radiometers can measure the canopy reflectance. CropScan (MSR85, CropScan Inc., Rochester, MN) is a hand held or vehicle mounted proximal sensor that is configured with eight wavelengths (460-810nm). CropScan has been used extensively to measure canopy reflectance in response to crop N status (Ma et al., 1996; Osborne et al., 2002; Rambo et al., 2010a; Shanahan et al., 2001). Rambo et al. (2010a) found CropScan could detect N differences in corn among increasing rates (0-240 kg N ha^{-1}). This was reported only during mid-season (v10), not early (v6) or late season (R1). Ma et al. (1996) used CropScan to distinguish between N treatments (0,100, and 200 kg N ha^{-1}) in corn. They found treatment effects over three collection dates (preanthesis, anthesis, postanthesis) which could help predict N deficiency throughout the growing season or predict potential grain yield. Ma et al. (1996) also found a strong correlation between NDVI, obtained using CropScan, and field greenness (a product of chlorophyll meter readings [SPAD] and leaf area). Detection of N stress in grain sorghum near growing point differentiation, and certainly before flowering, will be essential to enable corrective actions.

In addition to canopy reflectance, chlorophyll meters have been used to detect N deficiency in plants (Wu et al., 2007). The hand held SPAD 502 chlorophyll meter is a spectrophotometer that measures absorption of red and infrared wavelength at points on individual leaves, which is known to correspond with chlorophyll levels in the leaf (Bullock and Anderson, 1998; Reyes et al., 2017; Uddling et al., 2007; Yu et al., 2010; Yu et al., 2012). In addition to chlorophyll estimation, chlorophyll meters are capable of differentiating between N sufficient and deficient corn (Rambo et al., 2010a). While manual measurements from individual plants may not be the most efficient way to assess field variation of crop N status, it could be an essential, nondestructive method for confirming remotely sensed data.

In contrast to nondestructive methods, plant nitrogen status can be assessed through measurement of petiole sap nitrate using a compact nitrate ion meter (NIM) (Wu et al., 2007). The NIM is a low cost, handheld nitrate ion specific electrode with a digital display. Plant petioles or midribs are removed and sap extruded using a device similar to a garlic press for measurement in the NIM electrode. NIM has been used in many vegetable and fruit crops to record the petiole sap nitrate concentration throughout the growing season (Anderson et al., 2016; Deitch, 2016; Hochmuth, 1994; Zhang et al., 1996). Although some tissue is removed for sap nitrate measurement, the test provides a quick low cost alternative to laboratory analysis. Moreover, NIM could be used to compliment proximal and remotely sensed field crops.

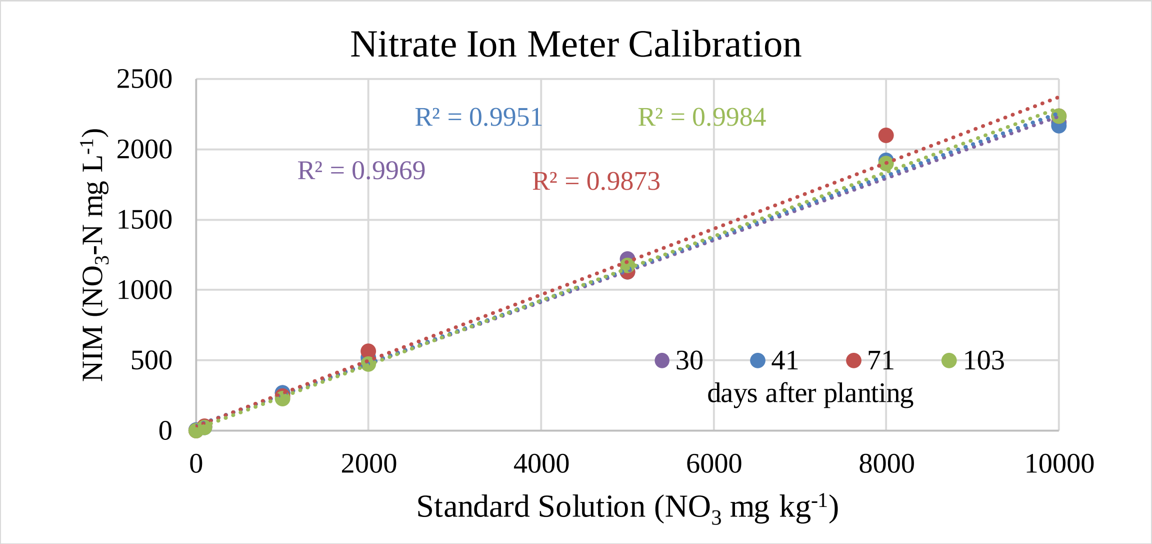
Many sensors are available for monitoring N status throughout the growing season for grain sorghum. Yet, minimal research has been done in Texas to monitor the canopy reflectance, and N status in grain sorghum. The objective of this study is to evaluate sorghum leaf and canopy level reflectance under contrasting starter fertilizer and N management practices. Relate leaf and canopy reflectance to midrib nitrate-N concentration, whole plant tissue N concentration, crop biomass and grain yield.

Materials and Methods

A two-year field study was led in Burleson County, TX at the Texas A&M AgriLife Research farm (30.543297, -96.435316) to evaluate crop sensors for grain sorghum under contrasting levels of N management. The plot design is described in detail in chapter two. Breifly, the study was arranged in a split plot design with four replications of fifteen fertilizer treatments for grain sorghum production during 2016 and 2017 growing season. Nitrogen rate (0, 112, 168, 224, 280 kg N ha^{-1}) was the main plot and the starter fertilizer practice (none, in furrow, 2x2) as the sub-plot. The treatments of the starter solutions were liquid ammonium polyphosphate (11-37-0) applied at 56 L ha^{-1} (in furrow), 168 L ha^{-1} (2x2) and no starter. Grain sorghum was planted on April 6, 2016 and March 22, 2017, both years using sorghum hybrid Dekalb DKS 51-01. The seeding rate was 160,550 seeds ha^{-1} using a four-row John Deere 1705 planter on 76.2 cm spacing. Plots were 3 m wide and 20.1 (2016) and 30.5 (2017) m in length. Contrasting sensors were used to monitor canopy reflectance and N status of grain sorghum throughout the growing season over a two-year period. Sensors evaluated included CropScan, SPAD, and NIM.

CropScan (Rochester, MN) was used four times in 2016 (49, 70, 93, and 113 days after planting) and five times in 2017 (32, 41, 83, 106, and118 days after planting) to measure canopy reflectance at 1.2 m above the canopy. All of the measurements were made between 10 am and 2 pm from the center two rows. In 2016, measurements were taken in point mode with reflectance values averaged for a single point in each plot. In 2017, measurements were taken in continuous mode, scanning the full length of each plot and generating the average reflectance for each plot. Continuous mode was used to capture variation within plots..

The Soil-Plant Analyses Development (SPAD) chlorophyll meter (Konica Minolta Inc, Osaka, Japan) was used to measure reflectance from points on 10 random leaves for each plot. There were four collection dates (30, 41, 71, 103 days after planting) with readings occurring between 10 am and 2 pm. For randomly sampled leaves in each plot, SPAD readings were taken at the mid-point of the most recently matured leaf. A standard reference reflectance disk was measured every 10 plots. Mean SPAD values for each plot are recorded.



From the same ten leaves used for SPAD measurements, leaf samples were collected for measurement of sap nitrate-N using a NIM (Horiba LAQUAtwin B-741, Kyoto, Japan). Leaf samples were kept on ice from the time of collection until NIM measurements. All NIM measurements were under laboratory conditions. The midrib was separated from each leaf and sap was expelled using a garlic press into a sample cup. Approximately 1 ml of sap was applied to the NIM electrode for measurement of NO_3-N concentration. Standard solutions (100 to 10,000 mg NO_3 kg^{-1}) were prepared using KNO_3 for calibration of the NIM (Figure 6). Standard checks of 2,000 and 5,000 mg NO_3 kg^{-1} were included every 10 samples for sap nitrate measurement.

Figure 6 Nitrate Ion Meter Calibration. Correlation between the NIM reading and standard solution at each collection date. P <0.001 for all dates.

A John Deer 3300 plot combine equipped with a Harvest Master (HM800) weigh system was used to measure grain yield, moisture, and test weight and were taken from the center two rows of each plot. Grain yield was adjusted to 14% moisture. In 2016 there were skips, due poor establishment. The skips were measured and deducted from plot lengths to correct actual harvested area. Plants were harvested by hand (cut at soil level) in a 3 m section of the first row of each plot. The plants were separated into grain and aboveground biomass to measure dry matter and N content. From the hand harvest panicle weight, grain weight, test weight, moisture, and seed size was measured to calculate grain yield. The grain was milled (2 mm) using a Wiley Mill 4 and submitted, to the Texas A&M Soil, Water, Forage Laboratory, for measurement of total nitrogen content. The aboveground biomass was weighed, chopped in the field using a forage chopper (Case 700), and subsample weighed and dried (65C) using a forced air oven for 36 hrs or until moisture loss was minimal. Dry matter and moisture content from the biomass was used to calculate dry matter yield for aboveground biomass. Dried biomass subsamples were milled using a Wiley Mill 4 (2mm) and sent to the laboratory for N analysis. The tissue and grain samples collected at hand harvest were submitted to the Texas A&M Soil, Water, Forage Laboratory to measure total nitrogen in biomass and grain samples. Total N (plant tissue and grain) was determined by high-temperature combustion (McGeehan and Naylor, 1988).

Soil cores were collected before the growing season of both years using a GSRPS Giddings Machine Company soil probe. Soil was sampled in 15 cm segments up to 60 cm in depth. The samples were sent to the Texas A&M Soil, Water, Forage Testing Laboratory for analysis. Mechlich III was used to extract phosphorus, potassium, calcium, magnesium, sodium, and sulfur and concentration measured by inductively coupled plasma (ICP) (Mehlich, 1984). A hydrogen selective electrode was used to determine soil pH in a 1:2, soil: deionized water extract. A conductivity probe was used to find soil electrical conductivity with the same soil: deionized water ratio as the soil pH (Schofield and Taylor, 1955). Nitrate N was extracted from the soil with 1 N KCL solution (Keeney and Nelson, 1982).

Statistical analyses were performed using SAS 9.4. The PROC GLM procedure was used to analyze variable of grain yield, NUE, biomass yield, grain and biomass N, CropScan NDVI, SPAD, and leaf nitrate content as a split-plot design with fertilizer rate as the main plot and starter fertilizer as the subplot. When appropriate, means were separated using L.S.D. The PROC CORR procedure was used to form a correlation matrix between variables grain and biomass yield, NUE, grain and biomass N, CropScan NDVI, SPAD, and leaf nitrate content. This was separated by date when necessary.

Results and Discussion

Canopy Reflectance - Normalized Difference Vegetative Index

Average NDVI was determined for grain sorghum in response to fertilizer treatments using CropScan in 2016 and 2017 (Figure 7). Mean NDVI values were fit to a nonlinear Gaussian model to estimate seasonal variation of NDVI. In 2016, NDVI measured using CropScan peaked at 70 days after planting and decreased until harvest. 2017 CropScan NDVI peaked at 87 days after planting with mean NDVI declining through harvest. Seasonal variation in NDVI for grain sorghum, measured using CropScan, followed similar patterns reported for other crops (Kim et al., 2015; Moges et al., 2007). Peak NDVI for grain sorghum in 2017 was 87 days after planting, which was 11 days after flowering occurred. Maximum seasonal NDVI is associated with maximum plant biomass and leaf area, which occurs near flowering for corn (Hatfield, 2014).

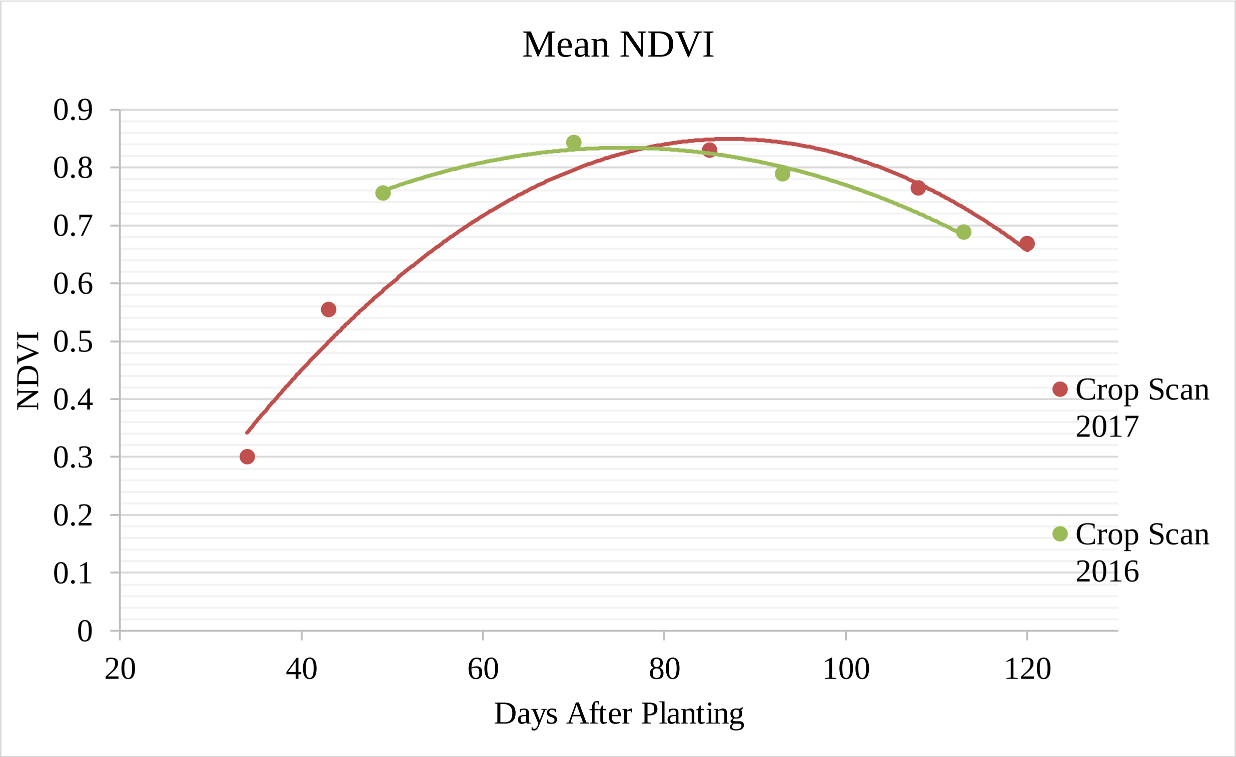


Figure 7 Mean Normalized Difference Index (NDVI). Average NDVI for the 2016 CropScan and 2017 CropScan over the growing season.

Although seasonal variation of NDVI measured using CropScan followed expected patterns, there was not a significant difference ($p > 0.01$) between N rates at any date during the growing season in 2016 or 2017 (Figures 8A & 8B). The lack of N stress in the field likely limited the ability to detect differences between increasing N fertilizer rates using NDVI. Moges et al. (2007) found similar results when evaluating NDVI and grain sorghum response to N fertilizer. Residual soil N and mineralization of N in crop residues limit sorghum response to N fertilizer therefore precluding comparison of NDVI for increasing N fertilizer rates. However, Ma et al. (2005) demonstrated significant variation of NDVI for corn under N limiting situations.

Grain sorghum NDVI in response to N fertilizer inputs should be evaluated under N limiting conditions to assess the potential for N fertilizer management.

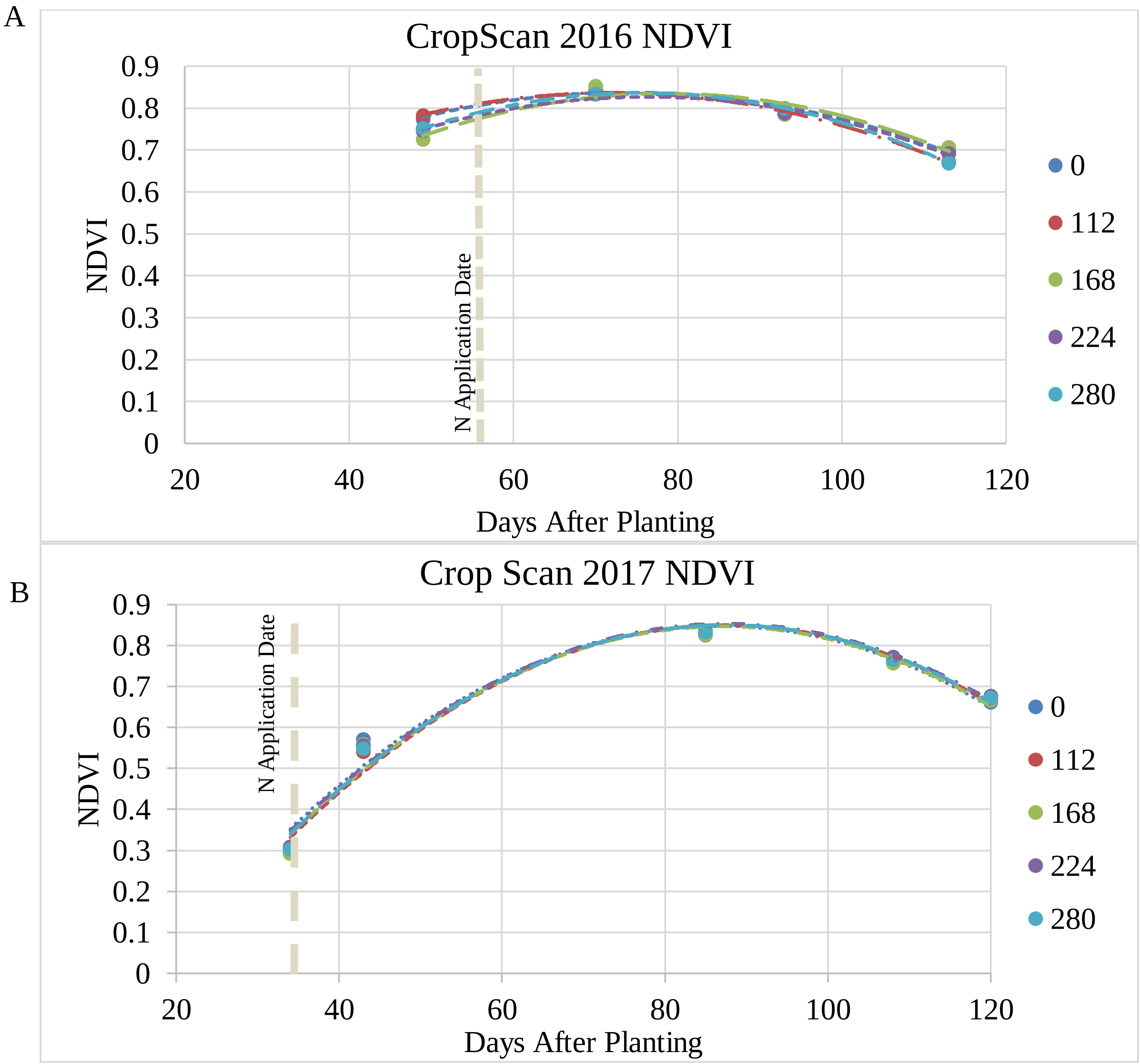


Figure 8 A) CropScan 2016 Normalized Difference Index (NDVI) B) CropScan 2017 NDVI. Average NDVI for the 2016 CropScan and 2017 CropScan over the growing season with increasing N rates. Application date was 56 days after planting in 2016 and 34 days after planting. Legend units are kg N ha^{-1}.

Despite the lack of response to N fertilizer rates, NDVI measured using CropScan did detect differences ($p < 0.05$) for contrasting starter fertilizer practices during 2017. At 32 days after planting, grain sorghum with in-furrow starter fertilizer had greater ($p < 0.05$) NDVI compared to the 2x2 and no starter applied practices (Figure 9A). At 41 days after planting, 2x2 and in-furrow starter fertilizer applications resulted in greater NDVI ($p<0.001$) than sorghum without starter fertilizer (Figure 9B). Placement of starter fertilizer, 2x2 or in-furrow, may have contributed to differences between starter fertilizers at 32 DAP and which was reduced by 41 DAP. Variation of NDVI was negligible among starter fertilizer practices by 83 days after planting.

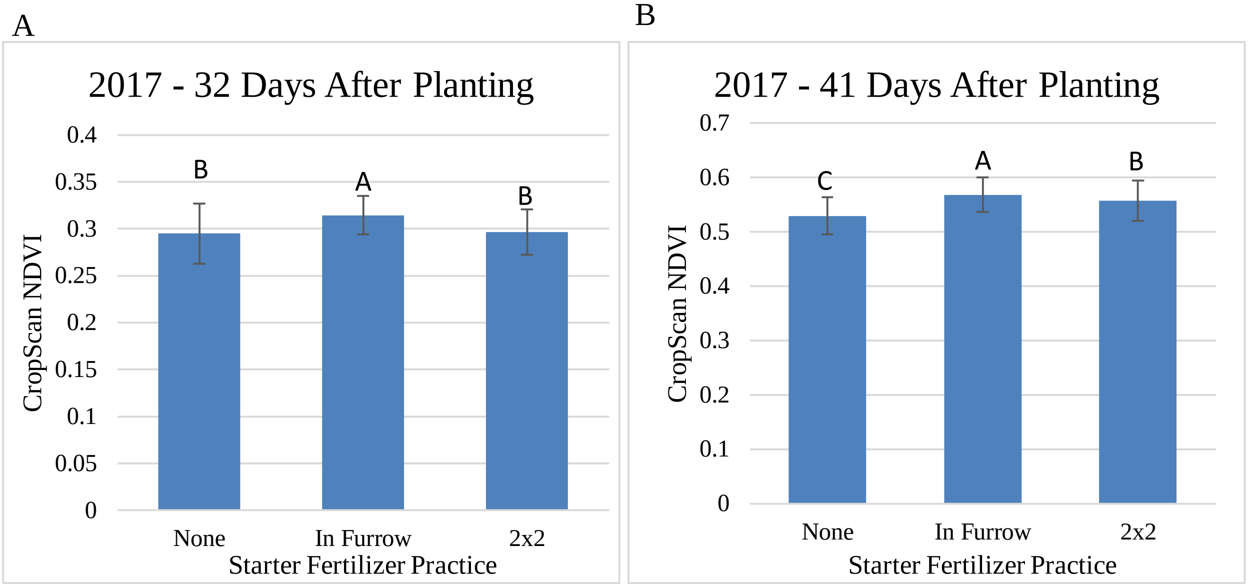


Figure 9 A) 2017 CropScan NDVI – 32 Days After Planting B) 2017 CropScan NDVI – 41 Days After Planting. Average NDVI of starter fertilizer treatments. Letters above bars indicate significant difference of starter practices at $p<0.05$. Errors bars represent one standard deviation.

Previous studies have shown correlation of sorghum grain yield and grain N content with NDVI as well other vegetation indices (Moges et al., 2007). Increasing N rates did increase grain yield and PNU in 2016 (table 5). Yet, NDVI measured with CropScan did not correlate with grain yield or PNU in the current study. Grain yield and PNU were greater for sorghum with no N applied in the current study compared to previous studies. Reduced variability in grain yield may have been due to significant amounts of residual N in the soil and mineralization of previous crop residues. This likely reduces the magnitude of NDVI differences measured across N rates and prohibits correlation with grain yield.

Table 6 Yield and Plant Nitrogen Uptake for 2016 and 2017. Average yield and PNU for contrasting N management practices. L.S.D. was used to compare means.

	Yield (kg ha^{-1})		**PNU (kg ha^{-1})**	
Starter	**2016**	**2017**	**2016**	**2017**
None	5201	7863	156.4	169.5
In-Furrow	5515	7964	137.5	175.1
2x2	6305	7931	151.5	182.4
Pr > F	0.0022	n.s.	n.s.	n.s.
N-Rate				
0	5156	7672	117.5	140.5
112	5526	8043	146.8	175.5
168	6258	7925	157.8	179.0
224	5356	7934	161.1	197.3
280	6072	8032	159.1	190.4
Pr > F	<0.01	n.s.	<0.01	n.s.
n.s. = not significant (>0.1), PNU (total plant N uptake)				

Handheld Sensors

Nitrate Nitrogen Concentration in Sorghum Midrib Sap

Sorghum midrib sap was obtained from the most recently mature leaf at four dates in 2017 for measurement of NO_3 concentration (Figure 10). Seasonal variation of NO_3-N concentration in sorghum midrib sap followed a sigmoidal pattern with increasing concentration leading up to flowering and declining concentrations through grain fill. Sorghum sap NO_3 – N concentration were greatest at 41 days after planting with a mean of 1593 mg L^{-1} and was lowest at grain fill with a mean concentration of 83 mg L^{-1}.

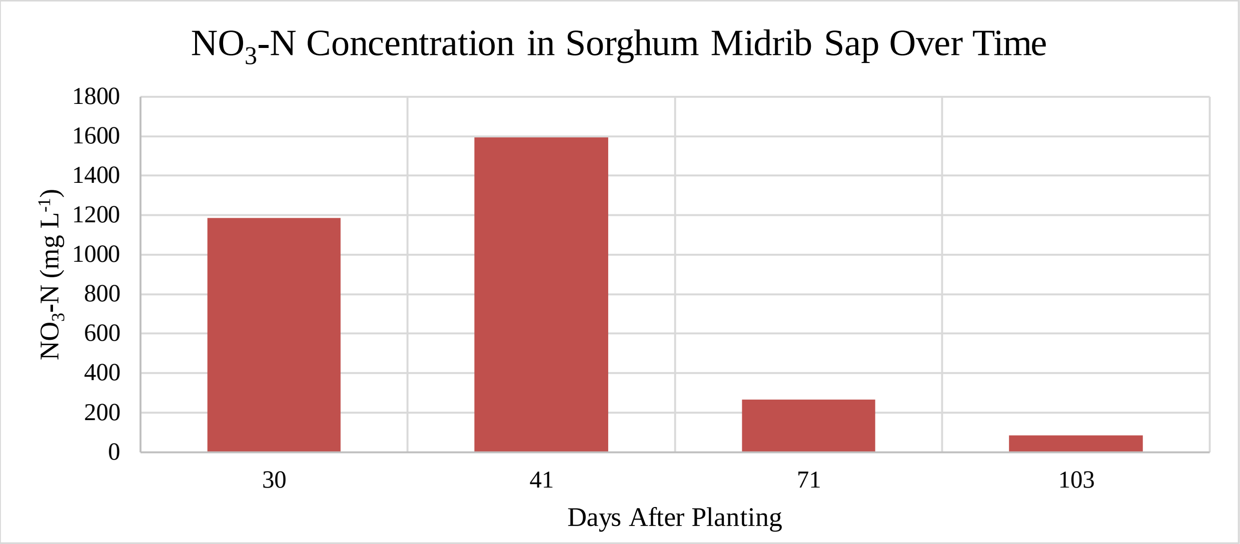


Figure 10 NO_3-N Concentration in Sorghum Midrib Overtime. Average NO_3-N from the NIM over the growing season.

Sorghum sap NO_3 -N levels were significantly ($p < 0.05$) increased by starter fertilizers early in the season (Figures 11A & 11B). Starter fertilizer increased sap NO_3 -N concentration 17% at the 6-leaf stage (30 days after planting) compared to sorghum without starter fertilizer. There was not a difference between the in-furrow and 2x2 applications at this time. Similarly, at the 9-leaf stage (41 days after planting) there was an increase in NO_3-N concentration for sorghum with starter fertilizer compared to sorghum without starter fertilizer. Sap NO_3-N concentration was increased 9 to 19.5% compared to sorghum without starter fertilizer.

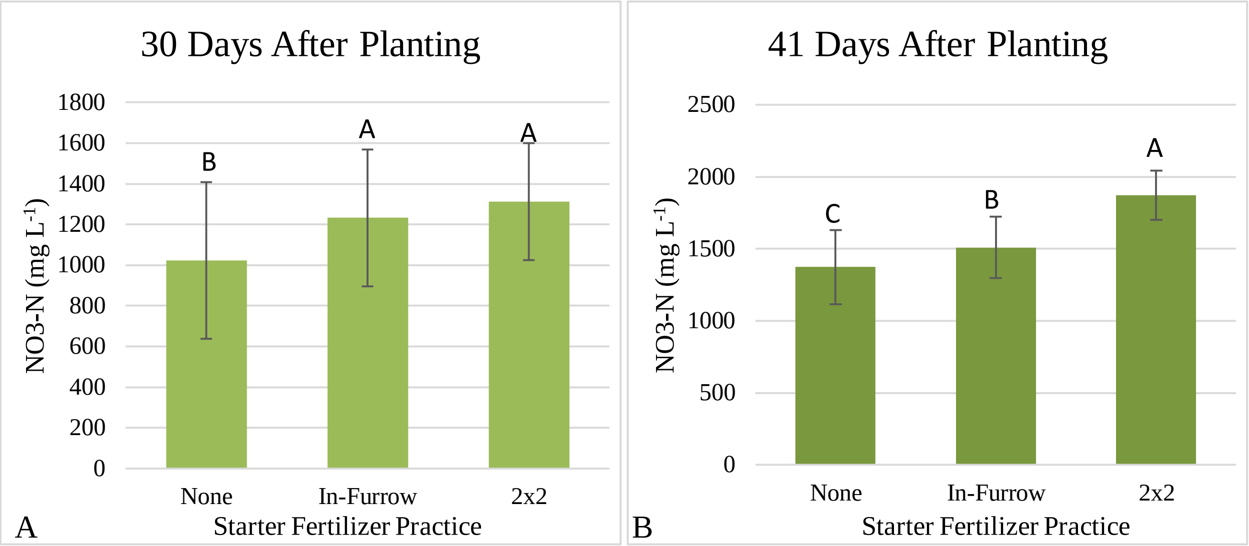


Figure 11 A) NO3-N Concentration in Sorghum Midrib Sap 30 Days After Planting B) NO3-N Concentration in Sorghum Midrib Sap 41 Days After Planting. Average NO3-N from the NIM when compared with starter fertilizer practices. Letters above bars indicate significance. Error bars represent one standard deviation.

Following application of N fertilizer at 34 days after planting, NO_3-N concentration increased with increasing N fertilizer rates (Figures 12A & 12B). At 71 days after planting, NO_3-N concentration was greatest in sorghum receiving a total of 168 and 280 kg N ha^{-1}. The lowest NO_3-N concentration was observed in the control (0 N) and N rate of 224 kg ha^{-1}. There was a 46% increase of NO_3 -N in the 280 kg ha^{-1} when compared to the control. Sap NO_3-N concentration at 103 days after planting was greatest where 280 kg N ha^{-1} was applied, although not significantly greater than 224 kg N ha^{-1}. Despite lack of response for canopy reflectance with starter fertilizer or increasing N fertilizer rates, differences were observed in sorghum sap nitrate concentration. Early season differences were due to starter fertilizers and later season differences were revealed following application of N fertilizer. The NIM shows promise and potentially greater sensitivity for monitoring sorghum nitrogen status during the season.

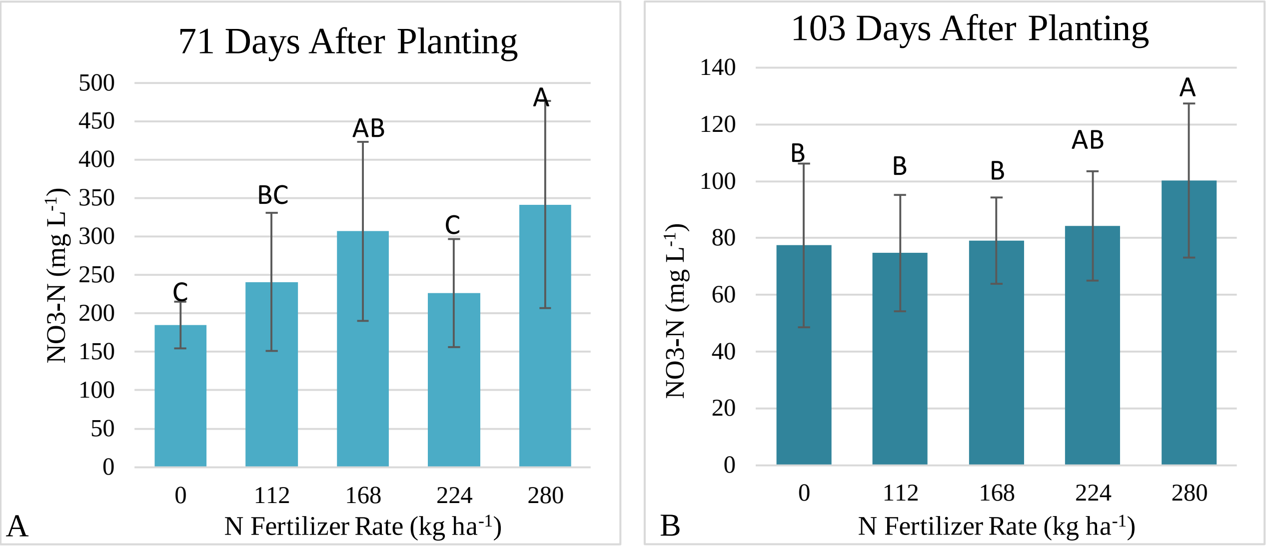


Figure 12 A) NO3-N Concentration in Sorghum Midrib 71 Days After Planting B) NO3-N Concentration in Sorghum Midrib 103 Days After Planting. Average NO3-N from the NIM when compared with increasing N rates. Letters above bars indicate significance at $p<0.05$. Error bars represent one standard deviation.

Chlorophyll Content in Sorghum

In conjunction with sap nitrate measurement, SPAD values were collected throughout the growing season (Figure 13). The mean SPAD value was 39 at 30 days after planting and peaked around 52 at 75 days after planting. Ma et al. (2005) found similar results in a N management corn study, where early seasons SPAD readings were 32 (V5) then increased to 65 by silking (R1). Values decreased at maturity.

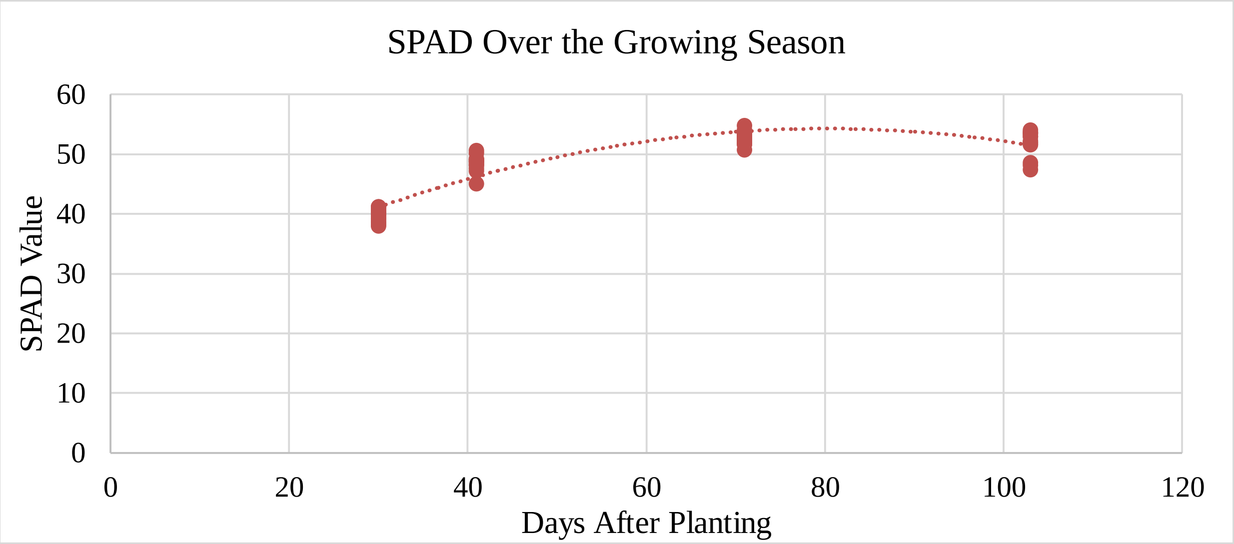


Figure 13 SPAD Over the Growing Season

Starter fertilizer treatments had no affect on SPAD values throughout the season ($p>0.05$). N fertilizer rates did have an affect on SPAD readings at two of the four collection dates. At 41 days after planting, application of 280 kg N ha^{-1} had a greater SPAD value than 0 and 112 kg N ha^{-1} (Figure 14A). At 103 days after planting, all sorghum receiving N fertilizer had significantly higher SPAD values ($p=0.0003$) than sorghum without N fertilizer (Figure 14B). However, there was no difference of SPAD values between N fertilizer rates. In contrast, Ma et al. (2005) found a linear increase in SPAD readings with increasing N rates for corn in two years out of a three years study. Similar to the current study, Rambo et al. (2010b) found that SPAD values did not differ between N rates above 80 kg ha^{-1} in a N management corn study. Comparing treatment affects at 41 to 103 days after planting, the ability of SPAD to detect differences in sorghum N status may be limited as time from N fertilizer application increases.

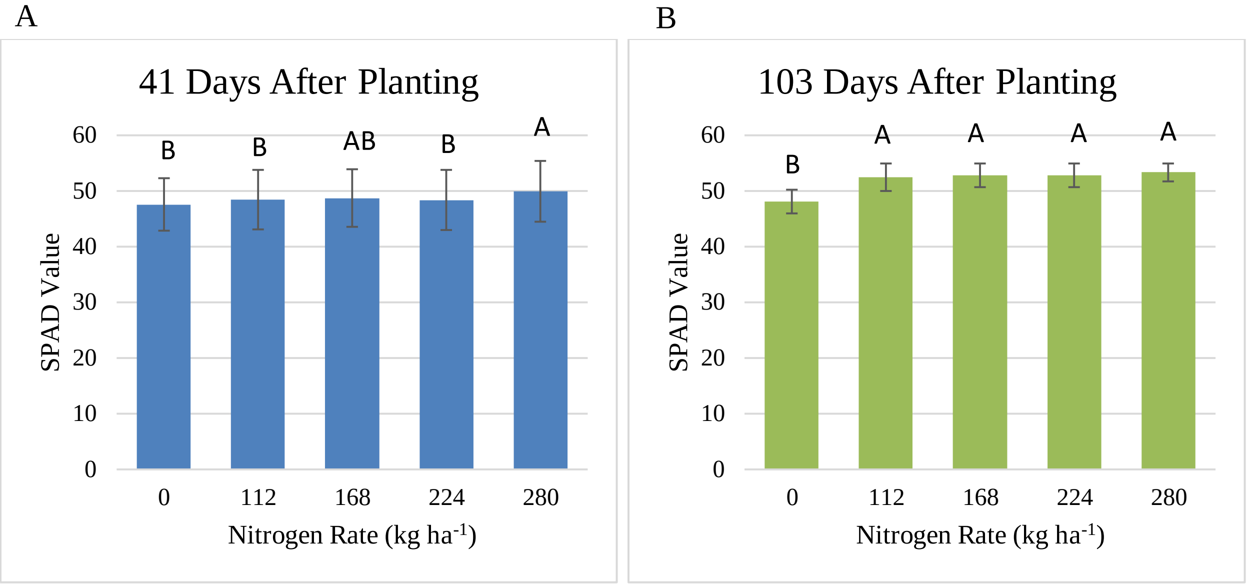


Figure 14 A) SPAD 41 Days After Planting B) SPAD 103 Days After Planting. Average SPAD Value when compared with increasing N rates. Letters above bars indicate significance at $p<0.05$. Error bars represent standard deviation.

Conclusions

Despite the lack of N stress in both years of the study, variation in NDVI, chlorophyll content, and sap NO_3-N was detected for grain sorghum in response to fertilizer management practices. CropScan NDVI and NIM did differentiate sorghum with starter fertilizer from sorghum without starter fertilizer at early growth stages. SPAD and NIM were able to detect differences in N fertilizer rates at later growth stages. NIM was the only instrument capable of detecting both early season impact of starter fertilizer and later season affects from N fertilizer rates.

NDVI has been used to monitor N status and predict yield of multiple crops over the growing season (Foster et al., 2017; Ma et al., 1996; Moges et al., 2007; Rambo et al., 2010b; Wang et al., 2016). CropScan was unable to detect differences in the N rates throughout the study. However, the lack of N stress in both years of the study likely reduced the ability of canopy level sensors to detect differences among N rates. Similar to previous studies, residual soil N and mineralization of N in soil likely contributed to significant plant available N pools and reduced sorghum response to N fertilizer.

Handheld sensors were also able to detect differences in the N rates and starter practices. The NIM was able to detect differences in NO_3-N concentration at all collection dates in response to fertilizer practices. Early in the season, the NIM measured differences in starter practices. Later in the season, NIM detected differences due to N fertilizer rates. The nitrate meter could be used to quickly obtain N status of the crop without time and expense required for laboratory results. While SPAD was not as sensitive as NIM, SPAD may be useful for detecting more severe levels of N stress.

CHAPTER V

CONCLUSIONS

Starter fertilizer practices have been studied extensively in many crops and production regions around the world, but there has been minimal research on how starter practices affect optimum N rate and timing, NUE, and yield in grain sorghum in Texas. Split applying N in grain sorghum could decrease N leaching, increase yield and increase NUE (Ameen et al., 2017; Buah et al., 2012; Mahama et al., 2014; Mahama et al., 2016; Maman et al., 2017; Tilman et al., 2002). Starter fertilizers that contain N could affect optimal timing for side-dress N application to grain sorghum. The timing of side-dress N application is critical for optimizing yield, increasing NUE, and decreasing environmental hazards (Bermudez and Mallarino, 2002; Cassman et al., 2002; Randall et al., 1985; Shrestha et al., 2010; Zotarelli et al., 2015). To assess in-season variation of crop N status with the ultimate goal of precision application and management of N fertilizer, canopy level reflectance has been evaluated using numerous spectral sensors for many different crops (Graeff and Claupein, 2003; Singh et al., 2017; Wang et al., 2017; Zhao et al., 2005). The ability of spectral sensors to identify N status and allow farmers to alter N management could result in increased grain yield and NUE in grain sorghum (Graeff and Claupein, 2003; Singh et al., 2017; Zhao et al., 2005).

In the present study, starter fertilizer applications increased grain yield in one of the two years regardless of N rate or timing of side-dress N. For the N rate study in 2016, application of starter fertilizer as a 2x2 band increased yield >14% compared to grain sorghum without starter fertilizer. For the N timing study in 2017, in-furrow and 2x2 application of starter fertilizer increased grain yield by 5.5% compared to sorghum without starter fertilizer. Improvements of grain yield due to starter fertilizer applications were observed despite moderate levels of soil test

P (> 40 mg kg^{-1}) and the presence of substantial soil N. This suggests that applying small amounts of N and P near or with the sorghum seed may improve early season uptake of N and P and result in greater early season growth as reported previously for corn and sorghum (Gordon and Whitney, 1995; Mascagni and Boquet, 1996). In addition, starter fertilizers containing N and P have been reported to reduce the time to flowering (Mahama et al., 2014; Mahama et al., 2016). The combination of greater early season growth and reduced time to flowering can result in greater grain yield for sorghum, although yield improvements are not consistent.

Despite the potential for starter fertilizers to improve grain yield, starter fertilizers did not affect the optimum rate or timing of N fertilizer and did not consistently improve NUE. An optimum N fertilizer rate of 168 kg N ha^{-1} was observed in 2016 regardless of starter fertilizer practice. The latest date for application of side-dress N without grain yield reduction was 56 days after planting during 2016, 26 days greater than the current recommendation (30 days after planting) (Vanderlip, 1993). The optimum N fertilizer rate was less than 110 kg N ha^{-1} and there was no grain yield reduction with increasing delay of side-dress N application during 2017. Significant amounts of residual soil N and mineralization of previous corn crop residues and moderate levels of soil test P likely limited the ability to influence optimum N rates or timing of side-dress N with starter fertilizer applications.

The inability to develop significant N stress through variation of N rate or timing of side-dress N created a challenging environment for remotely sensing variation of sorghum N status. Handheld sensors demonstrated greater ability to detect variation in sorghum N status than sensors measuring canopy level reflectance. NDVI measured using CropScan was able to identify differences in starter fertilizer practices early in the growing season. Yet, CropScan was unable to detect differences in the increasing N rates in either year of the study. In contrast to what other studies have found using CropScan NDVI with N management (Ma et al., 1996; Rambo et al., 2010a). In contrast, SPAD and NIM were able to identify differences in the N rates during 2017. SPAD detected variation in sorghum N rates at the two collection dates following side-dress N application. SPAD did not detect differences between starter fertilizer applications, despite increasing N and P amounts applied by contrasting starter practices. Yet, studies have shown SPAD to be a reliable source in detecting N status (Ma et al., 2005; Rambo et al., 2010b). In contrast, NIM was able to detect differences in NO_3 – N concentration from sorghum midrib sap at all four collection dates. Starter fertilizer practices increased midrib sap NO_3-N concentration measured before side-dress N applications were made. Following side-dress N applications, midrib sap NO_3-N concentration increased as N fertilizer rates increased. NIM demonstrated the ability to differentiate fertilizer practices despite the lack of significant N stress or deficiency of soil test P. Low cost NIM's may be useful for detecting N stress in sorghum across a wide range of growth stages and production systems. Moreover, it may provide rapid feedback as proximal and remote sensors are evaluated for tools for N management in grain sorghum.

Starter fertilizers can increase early season growth, canopy reflectance and uptake of N in grain sorghum. While not consistent, starter fertilizers applied in-furrow or near the seed can increase grain sorghum yield potential. However, it is unclear whether starter fertilizers will affect the optimum rate or timing of N fertilizer in grain sorghum based on the current study. Significant residual soil N and mineralization of soil N precluded observation of N stress need to fully express treatment affects. Likewise, this reduced the ability to detect N stress in sorghum canopies using various reflectance sensors. Additional research under lower fertility and minimal crop residues is needed to fully understand the impact of starter fertilizers on grain sorghum yield, optimum N rate, optimum N timing, and NUE in Texas.

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