EFFECT OF PREPLANT NITROGEN AND PHOSPHORUS APPLICATION METHOD AND SOURCE ON SORGHUM (SORGHUM BICOLOR L.) GRAIN YIELDS.

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2021

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ACKNOWLEDGEMENTS

I am highly appreciative of my advisor Dr. Bill Raun, not only for the opportunity, he gave me to pursue higher education but also for his constant guidance and skills he has imparted. It has been a real honor to work with him and I will forever be grateful for this.

I am also very grateful for the timely academic guidance and support that I received from members of my academic committee i.e. Dr. Brian Arnall, Dr. Jason Warren, and Dr. Paul Weckler.
I also want to thank my parents, Mr. & Mrs. Kisubi for the support they have given me throughout my stay here in the US. I also want to appreciate my family especially my husband and the children, the Wante's, who have been patient with me throughout this journey. I want to also thank my in-laws (auntie Monica) who have been there especially for my son while I was away, I can never be more grateful and the entire soil fertility team for all the support they have given me.
Lastly, I want to thank Dr. Stephen Mukembo who paved a way for me and introduced me to Dr. Raun for the very first time, It has been a real honor meeting you.
Thank you very much.

Name: EVA NAMBI

Date of Degree: MAY, 2021

Title of Study: EFFECT OF PREPLANT NITROGEN AND PHOSPHORUS
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Major Field: SOIL SCIENCE

Abstract: Nitrogen (N) losses can occur with different fertilizer sources and methods of application. Both N and phosphorus (P) are essential macronutrients for cereal production; however, there is little research done to demonstrate the effect of using different P sources and how these can be applied with N using different methods. The objective of this study was to determine NH4-N effects on sorghum growth when applied pre-plant with different phosphate fertilizers on sorghum grain yield using different methods of application in field conditions. To accomplish this study, we used a randomized complete block design with eleven treatments replicated three times. Urea ammonium nitrate (UAN) was used at the N source; diammonium phosphate (DAP) and liquid ammonium polyphosphate (APP) were used as P sources. The N-P application method was the dual placement of APP and UAN, Broadcast of DAP and UAN, and dribble surface band of APP and UAN. Grain yields were consistently higher when N was applied, 112.1 kg N ha^{-1} compared with the non-fertilized check. Dual placement of N and P increased grain yields by 35%. Also, the application of 20 kg P ha^{-1} gave better yield across sites. Application of N and P did not increase grain N except in two site years. The results were inconsistently affected by the method of application and fertilizer source that was shown by lack of effect in some years. N uptake was higher when N and P were dual placed and broadcast compared to the surface band.

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CHAPTER I

EFFECT OF PREPLANT NITROGEN AND PHOSPHORUS, APPLICATION METHOD AND SOURCE ON SORGHUM (SORGHUM BICOLOR L.) GRAIN YIELDS.

Abstract

Nitrogen (N) losses can occur with different fertilizer sources and methods of application. Both N and phosphorus (P) are essential macronutrients for cereal production; however, there is little research done to demonstrate the effect of using different P sources and how these can be applied with N using different methods. The objective of this study was to determine NH_4-N effects on sorghum growth when applied pre-plant with different phosphate fertilizers on sorghum grain yield using different methods of application in field conditions. To accomplish this study, we used a randomized complete block design with eleven treatments replicated three times. Urea ammonium nitrate (UAN) was used at the N source; diammonium phosphate (DAP) and liquid ammonium polyphosphate (APP) were used as P sources. The N-P application method was the dual placement of APP and UAN, Broadcast of DAP and UAN, and dribble surface band of APP and UAN. Grain yields were consistently higher when N was applied, 112.1 kg N ha^{-1} compared with the non-fertilized check.

Dual placement of N and P increased grain yields by 35%. Also, the application of 20 kg P ha^{-1} gave better yield across sites. Application of N and P did not increase grain N except in two site years.

The results were inconsistently affected by the method of application and fertilizer source that was shown by lack of effect in some years. N uptake was higher when N and P were dual placed and broadcast compared to the surface band.

1.1. Introduction

World N use efficiencies for cereal production remain very low with and where these efficiencies seldom exceed 33% (Raun and Johnson, 1999a; Raun et al., 2002). According to Raun and Johnson, (1999a), forage NUEs were reported to increase in winter wheat when 90 kg N ha^{-1} yr^{-1} was applied pre-plant, and the total N removed in a forage-only production system was also reported to double that found in grain (Thomason et al., 2000). The source of fertilizer N is one of the factors that was highlighted by Raun and Johnson, (1999) to affect the N use efficiency with NH_4^-N being more efficient than NO_3^-N.

Nitrogen can be lost easily via different avenues which have been discussed in detail by Raun and Johnson (1999a). Placement is an important factor affecting N utilization. A 20% increase in N-use efficiency for band placement compared with surface broadcast was found by (Rao and Dao, 1996). It has also been reported that subsurface urea bands can be more effective than surface applications for no-till corn (Blaylock and Cruse, 1992). Kelley and Sweeney (2007) also reported that the method of placement for fertilizer N in no-till cropping systems also influences N efficiency. They further reported that when urea-containing fertilizers such as urea-ammonium nitrate solution (UAN) were broadcast applied to the soil surface of high-residue cropping systems, ammonia (NH_3^+) volatilization losses can occur. According to reports by (Rao and Dao, 1996), deep placement of N can minimize volatilization or immobilization losses. However, these losses could be combated in various ways including using different N-sources. Ammonium (NH_4^+) has been reported to be less subject to leaching or denitrification losses and therefore N maintained as NH_4^+ in the soil should be available for late-season uptake (Raun and Johnson, 1999a). This work further noted that there was increased N uptake during grain-fill for N-responsive hybrids and a potential advantage of NH_4^+ nutrition for grain production. According to work by Raun and Johnson (1999), wheat N uptake was reported to increase by 35% when one-quarter of the N was applied as NH_4^+ compared to NO_3^-. Added studies showed that high yielding corn genotypes were unable to absorb sufficient NO_3^- during the grain filling stage and thus benefitted by ammonium nutrition (Fageria and Stone, 2006).

According to Sowers et al. (1994), NUE decreases with increasing N levels especially under dry soil conditions, this means that we have to come up with better methods of increasing N use efficiency. Nitrogen applied mid-season resulted in more efficient fertilizer use in 4 of 5 years compared with N incorporated before planting winter wheat (Raun and Johnson, 1999a). Several studies suggest that pre-plant N must be carefully managed to optimize grain yield and measures must be taken to reduce over application. According to Kelley and Sweeney (2007), many wheat producers in the eastern Great Plains prefer to pre-plant apply both fertilizer N (all or a portion of the total N requirement) and fertilizer P together in one field operation to facilitate more rapid and timely planting.

Phosphorus has also been highlighted as the second limiting nutrient in crop production after N, and it is estimated that P deficiencies can be found in nearly 67% of the world's crops (Dhillon et al., 2017). According to reports by Dhillon et al. (2017), P is abundant in the soil although the concentration of plant-available P in the soil solution is generally low. Phosphorus concentration in soil solution and P-buffer capacity is reported to be among the most relevant factors responsible for the availability of P to plants (Dhillon et al., 2017).

Nitrogen has been reported to increase P uptake and growth of plants, especially when N and P fertilizers are placed in a single, concentrated band in the soil (Leikam et al., 1983). According to

Leikam et al. (1983), the increase in P uptake with the application of N has been observed when N is applied as NH_4^+-N rather than NO_3^- -N, and he continued to report that the increased P uptake could be due to an increase in root growth and surface area in the region of the fertilizer band. Increased P availability has also been reported to result from acidity produced by nitrification of ammonium fertilizers in the retention zone, lowering of the rhizosphere pH due to exchange of H+ ions from the plant root for NH_4^+ ions in the soil, resulting in increased fertilizer P availability and uptake (Leikam et al., 1983).

Soil pH has also been reported to influence chemical properties and biological processes, including solubility, mobility, and availability of nutrients and trace metals (Dhillon et al., 2017). Dhillon et al. (2017) further reported that in alkaline soils, P can precipitate with Ca forming insoluble hydroxyapatite, octacalcium phosphate, and dicalcium phosphate whereas, in acidic soils, P can precipitate as minerals of Fe, and Al, and where both of these minerals decrease the availability of P for plant growth. Leikam et al. (1983) carried out a study in which he investigated the effect of N and P placement methods on P nutrition and final grain yield of wheat *(Triticum aestivum L.)* grown in the field and greenhouse. These results indicated that dual knife N-P applications gave higher leaf P concentrations and grain yields than other N-P application methods in many of the field studies when ammoniacal N sources were used. Many studies have been published on the method of application of N and P and how this affects yield in corn and winter wheat (Blair et al., 1970; Kelley and Sweeney, 2007; Leikam et al., 1983; Rao and Dao, 1996) however, limited information is available for sorghum production.

1.2. Literature Review

1.2.1. Nitrogen use efficiency as affected by N and P and method of application

Different factors have been highlighted to be the cause of the low NUE present for cereal production today. Among the factors highlighted by Raun and Johnson (1999a) are the N losses due to denitrification from applied N fertilizer ranging from 9.5% to 22%. They also reported that incorporation of straw and/or application of straw on the surface of zero-till plots can double denitrification losses.

It has also been reported that when urea fertilizers are applied to the surface without incorporation, losses of fertilizer N as NH3 can exceed 40% and this value can be greater with increasing temperature, soil pH, and surface residue (Raun and Johnson, 1999)). Rao and Dao (1996) reported that placement is an important factor affecting N utilization. They found an increase in N use efficiency of 20% when N was placed in bands compared to surface broadcast. They further noted that surface broadcast could reduce N immobilization and increase N uptake.

Majrashi et al. (2019) found grain sorghum yields with no-till to be greater or similar to conventional or reduced tillage in most years. This was mainly attributed to the reduced erosion, increased organic matter and increased precipitation infiltration, which leads to better utilization of nitrogen. In addition, grain yields were found to increase with increasing N rate. Aulakh and Malhi (2005) found 27% of the total yield response in corn was attributed to N and P application and 96% to the improvement in NUE.

In a separate study by Blaylock and Cruse (1992), it was reported that ridge tillage corn, fertilizer-N uptake, and yields were optimized with row injection, compared with broadcast or inter-row injections. Percent N derived from fertilizer, and percent fertilizer N recovered were significantly greater when N was injected versus broadcast N. They later concluded that point injection of N fertilizer can improve N-uptake efficiency over broadcast methods in ridge-tillage corn, but the importance of injection position was not substantiated.

1.2.2. Grain yield as affected by N and P and method of application

As noted, earlier N is an important nutrient when it comes to cereal production. The concept of the method of application has been demonstrated in several crops including winter wheat, barley, and corn (Rao and Dao, 1996). Therefore, a lot of the literature being used in this study is related to crops other than sorghum.

It has been reported by Khosla et al. (2000) that in studies that were conducted in the 1980s, placement methods for no-tillage corn production in the mid-Atlantic region and the Great Plains found that similar N application rates of UAN produced lower yields versus injected or surface-banded UAN. Knifed N-P-K applications at planting in sorghum have also been reported to increase grain sorghum yields relative to broadcast applications in high residue systems (Khosla et al., 2000). This study also evaluated whether or not preplant broadcast N applications are as efficient as band placed and side-dress N application used together. They found that for soils testing low in N, a starter band in conjunction with side-dress N applications resulted in higher yields.

According to a study carried out by Kelley and Sweeney (2005), wheat grain yields were found to be significantly greater with a preplant knife application of UAN compared with broadcast in both reduced and no-till systems when wheat followed grain sorghum or soybean. They also found that yields were increased when N was knife applied compared to surface broadcast. In a separate study by Kelley and Sweeney (2005) on tillage and urea ammonium nitrate fertilizer rate and placement effects on winter wheat following grain sorghum and soybean, grain yields were greatest in cropping systems where high-N-rates were knifed beneath the surface. In this same study, plant N uptake responses indicated that grain yield differences were primarily related to greater immobilization of both fertilizer and soil N following grain sorghum, compared with soybean, and to better utilize subsurface-knifed N verses surface-broadcast N.

In another study, banding liquid fertilizer UAN showed a significantly higher yield in corn compared with surface broadcast and the difference was attributed to the facilitation of N movement deeper into the soil profile thus decreasing the potential for loss due to denitrification and immobilization (Lohry, 1998; Rao and Dao, 1996). The improved performance of UAN in a surface band application compared to broadcast has also been attributed to increased nutrient concentration and diminished volatilization of NH_3 from urea in solution (Kelley and Sweeney, 2007; Lohry, 1998).

In a study conducted by Kelley and Sweeney (2007), yield was found to be higher when UAN was subsurface knifed (3.37 Mg ha^{-1}) compared to when surface applied through broadcast (2.92 Mg ha^{-1}) and therefore concluded that subsurface application has the potential to increase yield significantly both in no-till and in crop rotations.

Additional research by Rao and Dao (1996) found that fertilizer bands applied beneath the seed row resulted in 8% and 3% increased yield versus broadcast and fertilizer bands between rows. However, they also mentioned that the final grain yield and grain N content were not affected by the method of N placement in the plowed plots, which implies that the residue from no-till plays a role when deciding on the method of fertilizer placement. Other work by Rao and Dao (1992) found that placement of N in a narrow band on the soil surface in the spring improved nitrate reductase (NR) activity levels, and grain yields were related to NR activity levels. Rao and Dao (1992) concluded that placement of N in narrow bands increased N-use efficiency by increasing N reduction and assimilation but had little effect on the yield of grain and straw in both tillage methods. Buah et al. (2012) did not find any significant interactions between N, P, and K applications. However, applying only P increased yield by 14%, and similarly, N affected yield in a quadratic manner.

Sweeney (2016) found an increase in corn yield by 10 to 15% when fertilizer was applied using the subsurface band (knife) compared with the surface band (dribble). Sweeney (2016) suggested that the increase was due to an increase in kernel weight and the number of kernels/ear, the response was more prominent in years not affected by severe drought. Lamond et al. (1991) also found that the knife application of UAN in high-residue conservation-tillage conditions is more superior to broadcast or dribble applications by producing 940.65 and 627.1 kg ha^{-1} more grain per year than the broadcast and dribble placements, respectively. Lamond et al. (1991) also reported that knifed applications consistently produced higher N concentrations in leaf tissue and grain, which was later transformed into a higher apparent N use efficiency. With regards to the method of placement of N, Malhi and Nyborg (1990) carried out a study to compare methods of placement of fall-applied urea under zero tillage for yield, N use efficiency, N uptake, and recovery of applied N of barley. In this study, they found that broadcasting gave the least N uptake and percent recovery of applied N. Band placement in rows 22.5-cm apart markedly improved the efficiency of fall-applied N. From their study, they concluded that the efficiency of fall-applied N under zero tillage could be improved by placing N fertilizer in bands.

The N source is also one of the factors that have been highlighted by various authors to determine the N use efficiency in cereal crops including sorghum (Raun and Johnson, 1999; Sommer and Jensen, 1994). Significant loss of ammonia from surface-applied urea was negligible when ammonium nitrate was the fertilizer source (Sommer and Jensen, 1994). Gordon et al., (1993) did not find any differences in grain yield when N was applied by surface dribble compared with surface broadcasting. No differences occurred in grain yield, grain N concentration, or amount of N removed in the grain when either anhydrous ammonia or UAN was knife-injected. They later concluded that yield was unaffected by application method x N rate interactions.

According to a report by Fageria et al. (2009), assimilation of NO_3-N requires an energy equivalent of 20 ATP mol^{-1} NO_3, whereas NH_4^+ assimilation requires only five ATP mol^{-1} NH_4^+. This energy saving can be beneficial to the plant in terms of preserving energy for production if the plant is supplied with NH_4^+. According to Ortas et al. (1996) in a study to investigate the effect of NH_4^+-N and nitrate (NO_3^--N) forms, and the rate of P and mycorrhiza did change rhizosphere pH and P uptake. They also found that when N was supplied as NO_3^--N, rhizosphere pH increased gradually with increasing P addition. The addition of N in the form of NH_4^+-N has been reported to increase P uptake by plants compared to when N is supplied as NO_3^- (Gahoonia et al., 1992; Ortas et al., 1996).

1.2.3. Phosphorus and phosphorus use efficiency

Phosphorus has been identified as the most deficient essential nutrient after N (N) in most agricultural systems. (Dhillon et al., 2017; Mosali et al., 2006). It is an essential element when it comes to storage and transfer of energy in the form of Adenosine triphosphate, ATP, Adenosine Diphosphate, ADP and it's a structural component of nucleic acids, coenzymes, phospholipids, and nucleotides (Hyland et al., 2005; Mosali et al., 2006). According to Mosali et al. (2006), P originates from the weathering of soil minerals and other stable soil geologic materials and exists in both organic and inorganic forms with the inorganic fraction being dominant. The inorganic forms of P are dominated by hydrous sesquioxides, amorphous crystalline aluminum and iron phosphates in acidic soils and as calcium phosphates in alkaline soils (Mosali et al., 2006). Dhillon et al. (2017) mentioned that P is abundant in the soil although the concentration of plant-available P in the soil solution is generally low.

Several authors have also mentioned that the amount of available soluble P depends on several factors. These factors have been highlighted to include; pH, the extent of contact between the precipitated P and the soil solution, the rate of dissolution and diffusion of solid-phase P, time of reaction, organic matter content, temperature, and type of clay present (Dhillon et al., 2017; Dibb et al., 1990; Leikam et al., 1983; Mosali et al., 2006). Phosphorus concentration in soil solution and P-buffer capacity are among the most relevant factors responsible for the availability of P to plants (Dhillon et al., 2017).

In alkaline soils, P can precipitate with Ca forming insoluble hydroxyapatite, octacalcium phosphate, and dicalcium phosphate while in acidic soils; P can precipitate as minerals of Fe, and Al. Both of these minerals decrease the availability of P for plant growth (Dhillon et al., 2017; Dibb et al., 1990; Sato et al., 2005). Dhillon et al. (2017) reported that crop production is reduced due to P deficiency on an estimated 5.7 billion hectares of land, and due to the non-renewable nature of P resources, appropriate management is needed to lengthen the life span of phosphate reserves.

According to Mosali et al. (2006) on reports carried out on winter wheat, P fertilizer use efficiency (PUE) averaged 8% when P was broadcast incorporated and 16% when P was either knifed with anhydrous ammonia or applied with the seed. Dhillon et al. (2017) estimated P use efficiency for cereal production at only 16%, which implies that more has to be done to be able to manage P for improved plant growth. Mosali et al. (2006) further mentioned that although inorganic fertilizers are readily available, they are slowly converted to unavailable forms due to precipitation, and during early growth stages, plants may utilize the readily available form, while they compete for the slowly available forms in later stages of growth. According to Mosali et al., (2006), P deficient soils may require pre-plant broadcast-incorporated rates of 11 to 22 kg P ha^{-1} to correct the deficiency in either wheat or corn. In work done by Fiedler et al.(1989), he reported that banding of low P fertilizer rates close to the seed on soils that are low in available P can be more effective than broadcast P applications at the same rate. He also went on to mention that soils containing high to medium available P levels might not show any significant response to the method of application.

Aulakh and Malhi (2005) mentioned that the application of P and N results in a synergistic relationship. They further noted that in P deficient soils, application of N alone could have little effect on the yield of the crop but both P and N application could increase the yield significantly.

According to work done by Kelley and Sweeney (2007) on the placement of preplant liquid N and P fertilizer in winter wheat following different summer crops, grain yields were found to be greater for

N-P knife application with an average of 3.68 Mg ha^{-1} over 3.40 $Mgha^{-1}$ for surface broadcast. Raun et al. (1987) found Urea phosphate to provide greater yields, grain P uptake, and total P uptake than ammonium polyphosphate and diammonium phosphate at a calcareous site when applied in bands to the side, broadcast, and or dual placed.

1.2.4. Behavior of UAN, DAP, and APP

Choosing the source of fertilizer is one of the key factors that need to be considered, different nitrogen fertilizers behave differently when in the soil which can lead to either subsequent loss or utilization. Application of urea fertilizers to the surface without incorporation may result in losses of fertilizer N as NH_3 that can exceed 40% and these losses can be even greater with increasing temperature, soil pH, and surface residue (Raun and Johnson, 1999). The authors went ahead to mention that the losses can be significant especially when fertilizer is applied at rates that are in excess of that needed for maximum yield in cereal crops and this is mainly due to NO_3 leaching. Raun and Johnson (1999) also reported that assimilation of NO_3^-N also requires a lot more energy compared to NH_4^+-assimilation (20ATP-NO_3 and 5ATPs for NH_4^+). They further went ahead to mention that the energy reserve will result in better energy saving and increased dry matter production. Urea has also been noted to cause damage to the seedling if applied too close to the seed; this happens following pH increase after application caused by hydrolysis of urea resulting in ammonia release. This, therefore, implies that NH4-N based fertilizers can be a better choice in some cases since it is less subject to leaching and if maintained as NH4 in the soil, it should be available for late-season uptake (Raun and Johnson, 1999). Urea ammonium nitrate is made by mixing urea with ammonium nitrate solution and its commercial concentration varies with geography (Series, 2009). When UAN remains on the surface of the soil for extended periods without incorporation, soil enzymes will convert the urea to NH4, a portion of which can be lost as ammonia gas. In addition, because of the lower N in urea and ammonium form, volatilization losses per pound of N from UAN will be lower than for urea (Series, 2009).

Diammonium phosphate contains readily available sources of N (Series, 2009), and where some authors have recommended that since there can be seedling injury while using DAP, banding should be limited (67 kg ha^{-1} DAP or 34 kg ha^{-1} urea plus N from DAP) (Series, 2009).

There is a wide gap in research that documents the significance of the application both nitrogen and phosphorus using different methods specifically in sorghum. Most of the work done focuses on how N and P application affects P uptake and leaf tissue concentration. Therefore, the main objective of this study was to evaluate grain yield and nitrogen content, and N-uptake of sorghum when N and P are applied pre-plant using different methods.

1.3. Materials and Methods

1.3.1. Experimental site and design

Field experiments were established in two different locations the Efaw Research Farm (EFAW) and Lake Carl Blackwell Research Farm (LCB) across the years of 2018, 2019, and 2020. The EFAW farm is near to Stillwater Oklahoma, while the LCB farm is near Perry, Oklahoma. Soil classification at the Efaw research station is Ash port silty clay loam (fine-silty, mixed, super active, thermic Fluventic Haplustolls) and at LCB the soil classification is Pulaski fine-sandy loam (coarse/ loamy, mixed nonacid, thermic, Typic, Ustifluvent) USDA / NRCS soil taxonomy. Both locations managed utilizing best management practices suggested by Oklahoma State University and the Oklahoma Cooperative Extension Service.

A randomized complete block design with three replications and eleven treatments was used at all sites. Each plot measured 6 m x 3 m and was separated by an alley of 3 m in width The plant population was estimated at 86,486 seeds ha^{-1} with a row spacing of 0.72 m. Each plot received a total of 112 kg N ha^{-1}. The method of placement for N and P in the form of UAN (32-0-0), DAP (18-46-0), and APP (10-34-0) and three different rates. Methods of placement were dribble surface band (DB) 5 cm to the side of the seed, broadcast (BC) on the surface, and dual placement (DP) 5 cm to the side and 5 cm below the seed.

1.3.2. Experimental management and data analysis

Prior to planting, soil samples were taken per individual treatment to determine the amount of N and P in the soil. Ten cores were taken at a depth of about 15 cm per plot. The samples were packed in individual bags and labeled for each of the treatments. The samples were then dried in the oven overnight at 60^{o}C and later on ground to pass a 2 mm sieve. The soil pH of the different soil samples was determined by adding water to the soil in a 1:1 ratio (soil: water suspension). A glass electrode was then used to measure the pH and buffer index (Sikora, 2006; Sims, 1996). NO_3-N and NH_4-N were extracted using a 1 M potassium chloride solution and then quantified using the Flow Injection Auto analyzer (LACHAT, 1994). Plant-available P and K were extracted using Mehlich 3 solution (Mehlich, 1984). The amount of P and K were determined using a Spectro CirOs ICP spectrometer (Soltanpour et al., 1996). A detailed description of soil analysis results are presented in table (Table 1.1 & 1.2)

Treatment 1 received neither N nor P, treatment 2 received N but no P, and treatments 3 to 5 received P broadcast. Treatments 6 to 11 all received ammonium polyphosphate applied in dribble surface bands and dual placement respectively (Table 1.4). All the treatments were applied preplant for both N and P fertilizer sources. Greenseeker Normalized Difference Vegetative Index values (NDVI) were collected at different growth stages up until heading. Where NDVI = (NIR-red) / (NIR+Red), NIR reflectance determined at 780 nm and red reflectance at 660 nm. General growth characteristics of the crop were also observed and recorded in pictures (Figure 1.7 & 1.8).

Grain yield samples were collected and analyzed for N content. Sorghum grain was harvested using a combine from each plot and moisture content adjusted to 12%. Small samples of approximately 0.5 kg were collected and oven-dried for 48 hours to achieve less than 1% moisture. The samples were ground and then rolled within small bottles with 4 stainless steel rods for 24 hours to obtain complete sample homogeneity. Subsamples of ~150mg were collected to analyze for grain N using the LECO TruSpec CN628 dry combustion analyzer (LECO Inc., St. Joseph, MI, USA). Grain N uptake was determined by multiplying the percent grain N with the harvested grain yield (see equation below).

Grain N uptake = Harvested yield × Percent grain N content

The results were analyzed using SAS 9.4 software and a generalized linear model (SAS Institute, Cary, NC, USA). To determine treatment differences, the least significant difference (LSD) mean separation procedure at an alpha level of 0.05. Single degree of freedom contrasts were conducted to evaluate impact of treatments as well. Also, R statistical package was used for data visualization using.

1.4. Results and Discussion

1.4.1. Grain yield

At the EFAW site, grain yield ranged from 1.05 to 2.47 Mg ha^{-1}, 2.89 to 4.16 Mg ha$^{-1,}$ and 4.36 to 7.08 Mg ha^{-1} in 2018, 2019, and 2020 respectively (Table 1.6, 1.7 &1.9). Single degree of freedom contrasts did not show any significant differences in grain yield due to method of application and P rate in the different years. Looking at individual treatments, the application of 20 kg ha^{-1} P resulted in a higher yield to 10 and 30 kg ha^{-1} P. In 2019, we observed a higher yield when we applied 20 kg ha^{-1} of P using the broadcast and dribble surface band method. Schlegel and Bond (2007) reported an increase in corn yields at low starter P rates compared with broadcast while at high rates, corn yields were significantly greater with starter plus broadcast application than with a high rate that was only deep-banded. Preston et al. (2019) reported better response with P rate of 39 kg P ha^{-1} corn yields were similar for deep-band and broadcast P fertilizer under strip-tillage and starter fertilizer increased yield for a high-yielding, low soil test P location

In 2020, grain yield was generally highest with the dual placement method and 20 kg P ha^{-1} resulted in a higher yield with the dual placement method. In general, grain yields were relatively low at the EFAW site in 2018. Other researchers have found similar trends even with the application of fertilizer. Cabrera et al.(1986) found an increase in tilllering and early dry matter production when the wheat seed was surface banded with fertilizer and that did not translate into higher yields. Environmental factors cannot be overlooked as was discussed by Raun et al. (2019). The high temperatures could have caused nitrogen losses due to various methods like denitrification; volatilization since planting was later in June when temperatures were higher. This agrees with work done by Raun and Johnson (1999). Also, failure to synchronize planting with early rainfall (Table 1.11) (Figure 1.1 & 1.2) caused a decrease in grain yield.

At the LCB site, grain yield ranged from 2.26 to 4.56 Mg ha^{-1}, 4.75 to 7.36 Mg ha^{-1} in 2019 and 2020 respectively (Table 1.8 & 1.10). Single degree of freedom contrasts showed that there were significant differences in yield due to the dribble surface band and dual placement methods. In 2019, the dual placement method had a significantly higher yield compared to the other methods of application. In general, the application of N and P resulted in higher yield compared to the application of N (Figure 1.3 & 1.4). The dual placement method resulted in a higher yield of 35%. Other researchers have also found better yields when N and P are applied together. The reason for this is that P tends to become fixed by certain cations like calcium making it unavailable for plant use. Therefore, the application of both N and P makes P available whereby during the nitrification process, which leads to the formation of NH_4^+ ions, hydroxyl ions are released in solution react with calcium making way for the release of P in the soil. Leikam et al. (1983) found that yield increased when N and P were dual knifed compared to when separated in the soil. These results are also consistent with work conducted by Raun et al. (1987) in which they reported higher corn yields when P and N were dual placed compared to banding. Also, the results indicated that broadcast N and P fertilizer gave higher yields in some years, EFAW 2018 and 2019, and 2020 for both locations. This was also consistent with work done by Raun et al. (1987) which was attributed to the root activity near the surface of the soil residue interface.

Also, the results indicate that in all site years, grain yield in the N and P fertilized trials was higher compared to treatments that received only N. This is supported by research done by Aulakh and Malhi (2005) where they found treatments that received nitrogen alone to have little impact on yield compared to treatments with N and P. The reason for this is that N and P have a synergistic effect when applied together. Kelley and Sweeney (2005) also reported high yields for cropping systems for high N-rate when applied by the subsurface knife method. Kelley and Sweeney (2007) also found higher grain yields of 3.68 Mg ha^{-1} when N and P fertilizer was dual knifed in wheat following summer crops. Stecker et al. (1993) found an increase in grain yield of corn when nitrogen was knife applied compared to broadcast and dribble application.

In contrast, Lohry (1998) found 1.41 Mg ha^{-1}, 3.36 Mg ha^{-1}, and 7.39 Mg ha^{-1} increase in yields of corn, wheat, and bromegrass respectively when fertilizer was applied by surface banding in reduced tillage compared to broadcast. Randall and Hoeft (1988) found a better response to band applications in small grains when fertilizer is placed with the seed or knifed into a 4 to 5 in. depth especially under drier conditions. However, Sweeney and Ruiz Diaz (2018) did not find any differences in grain yields when N knifed compared to broad cast and dribble surface band applications.

1.4.2. Grain N

At the EFAW site, grain N concentration was significantly different in 2018 and 2019 respectively (p = 0.0043, p= 0.0025) (Table 1.6 & 1.7). Also, as yield increased across years, grain N levels decreased with 2018 having the highest grain N content and 2020 having the lowest (Figure 1.5 & 1.6). This is attributed to the dilution of nitrogen as the grain yield increases.

At the LCB site, grain N was significant in 2020 (p=0.0004) (Table 1.10). Also comparing the two site years at this location, grain N was highest in 2019 when the yield was relatively lower compared to the 2020 site year. Single degree of freedom contrasts showed significant differences in grain N with the broadcast method and the dribble surface band method. Also, the application of N and P did not seem to affect grain N content. In general, when grain yield increased, grain N content was found to be lower. Lollato et al. (2019) reported a negative exponential relationship between grain N content and grain yield. They further noted that co-application of N, P, and K resulted in a decrease in grain N content compared to when only N and K were applied. On the contrary, Kelley and Sweeney (2007) reported a positive correlation between wheat grain yield, grain N, and N uptake. They also found N uptake to increase with N rate when fertilizer was applied using the knife method compared to broadcast and surface band method.

1.4.3. N-Uptake

In general, there was no significant difference in N uptake across all years. In 2019 at the EFAW location, N uptake was observed to decrease with N rate when fertilizer was applied using the dual placement method. Also at this location, the broadcast method had increased N uptake compared to the dribble surface band. At LCB in 2019, there were significant differences observed when fertilizer was applied using different methods. The dual placement method resulted in higher N uptake than the band method by 1.6%. There was no evidence that the P rate resulted in higher N uptake. Similar to EFAW 2018, the broadcast method had slightly higher nitrogen uptake compared to the dribble surface band method in LCB 2020. Lohry (1998) found nutrient uptake to increase with surface banding over broadcast application of fertilizer. Schlegel et al. (2003) found a decrease in N uptake with an increase in N rate although an increase was observed when UAN was injected versus broadcast in wheat. Sweeney et al. (2018) found an increase in N uptake at the R4 corn stage with the knife application at low N rates although this was not the case at high N rates. They later concluded that improving total N uptake increased relative yield primarily by increasing kernels per ear, with lesser effects due to kernel weight and ears per plant (Sweeney et al., 2018)

1.4.4. Headcount

Head counts were collected in 4 out of 5 site years i.e. EFAW 2018 & 2020 and LCB 2019 & 2020. The number of heads were significant at both the EFAW and LCB site in 2020 (p = 0.002, p= 0.006) (Table 1.9 &1.10). Application of N and P resulted in increased number of heads at the EFAW site in both years that were counted. However, this was not the case at the LCB be site where we saw an increase with the broadcast method in 2020. Single degree of freedom contrasts showed that there were significant increase in number of heads when N was applied compared to zero applications of N. Sander et al. (1990) found knifed P, placed below tillage depth with little disturbance of the band area to result in greater residual value for grain sorghum following wheat than either seed or broadcast P. Ogunlela (1988) found that application of N and P enhanced grain weight per head, grain number, test weight and tilllering significantly but it was only N which enhanced 1000-grain weight and flag leaf area.

1.5. Conclusion

Method of fertilizer application and the source have a significant role in the yield of grain sorghum. The results indicate that in two of the site years, the dual application of APP and UAN resulted in a higher yield compared to the surface banding. Similar to dual placement, broadcast application of DAP and UAN resulted in higher yields in two site years although the yields were lower compared to dual placement. This is similar to what was discovered by Bushong et al. (2014) who found that the timing of N application was less significant in determining yield. In addition, P application was found to be beneficial in only years where moisture was less sufficient. The results were inconsistent both for fertilizer source and method of application. This is similar to what was found by Westerman and Edlund (1985). In general, the dual placement method can be beneficial in terms of concentrating nutrients close to the root zone where they can easily be taken up. Also, the application of UAN and P together plays a role in making fixed forms of P available for plant use by increasing the pH.

1.6. References

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Table 1.1. Initial soil test properties at EFAW in 2018

	2018				
	EFAW[I]				
Treatment	NO3-N	NH4+N	P	K	pH
1	0.1	2.6	34	213	5.6
2	0.1	1.2	33	215	5.8
3	0.1	1.3	29	212	6.5
4	0.1	1.7	25	214	6.3
5	0.1	1.9	28	215	6.1
6	0.1	1.9	28	210	5.8
7	0.1	1.4	26	200	5.9
8	0.1	1.5	31	224	6.2
9	0.1	1.2	28	216	6.1
10	0.1	1.3	28	217	5.6
11	0.1	1.3	28	218	5.7

[I] All units are in mg per kg except for soil pH

Table 1.2. Initial soil test properties for EFAW and LCB in 2019

	2019									
	EFAW[I]					LCB[I]				
Trt	NO3-	NH4+	P	K	pH	NO3-	NH4+	P	K	pH
1	0.2	1.8	24	181	5.7	0.2	1.5	32	123	5.8
2	0.2	1.4	26	164	5.6	0.1	1.2	18	101	5.9

3	0.2	1.4	30	195	5.8	0.1	1.5	18	123	6.2
4	0.1	1.4	37	153	6.1	2.9	3.6	30	132	6.3
5	0.1	1.3	32	150	6	0.1	1.8	39	142	5.7
6	0.2	1.4	35	227	5.6	0.1	1.2	27	132	6.1
7	0.1	1.3	39	171	6.1	0.2	1.6	15	115	6.2
8	0.1	1.4	34	142	5.8	0.1	1.7	48	133	5.7
9	0.1	1.6	32	140	5.9	0.1	1.6	56	163	5.6
10	0.1	1.3	25	145	6.3	0.1	1.3	25	126	6.3
11	0.1	1.2	25	144	6.2	0.1	1.1	18	142	6.1

[I] All units are in mg per kg except for soil pH

Table 1.3. Initial soil test properties for EFAW and LCB in 2020

EFAW[I]				
NO3-	NH4+	P	K	pH
0.6	1.1	78.1	138.6	5.7
LCB[I]				
0.6	0.8	29.6	92.7	5.8

[I] Units in mg per kg except for soil pH

Table 1.4. Treatment structure for evaluation of the effect of preplant nitrogen, phosphorus, source, and method of application on sorghum grain yields.

Trt	App.	Source	DAP	APP	UAN
			kg P ha^{-1}	kg P ha^{-1}	kg N ha $^{-1}$

1	Check		-	-	
2	P Check	UAN	-	-	112.1
3	Broadcast	DAP	10	-	103.1
4	Broadcast	DAP	20	-	94.5
5	Broadcast	DAP	30	-	85.7
6	Dribble surface band	APP	-	10	105.5
7	Dribble surface band	APP	-	20	98.9
8	Dribble surface band	APP	-	30	92.4
9	Dual placement	APP	-	10	105.5
10	Dual placement	APP	-	20	98.9
11	Dual placement	APP	-	30	99.1

Table 1. 5. Field activities conducted throughout the growing season

Year	2018	2019		2020	
Location	EFAW	EFAW	LCB	EFAW	LCB
Soil sampling	6/15/2018	4/22/2019	4/22/2029	04/1/2020	4/1/2020
preplant	6/15/2018	5/30/2019	4/29/2019	4/15/2020	4/16/2020
Planting date	6/15/2018	5/30/2019	4/29/2019	4/15/2020	4/16/2020
Sensing	6/27/2018	6/25/2019	6/20/2019	6/16/2020	6/16/2020
Headcount	9/25/2018	NA	9/1/2019	7/2/2020	7/30/2020
Harvest date	9/27/2018	9/20/2019	9/5/2019	8/10/2020	8/10/2020

Table 1.6. Grain yield, NDVI, grain N and N-uptake at the EFAW site in 2018

Treatment	Application method	NDVI	Grain N %	Grain yield Mg ha^{-1}	N uptake kg ha^{-1}	Heads ha^{-1}
1	No	0.35	2.01	1.52	30.5	42697
2	Broadcast	0.35	2.20	2.09	45.7	45747
3	Broadcast	0.35	2.07	1.05	26.7	54358
4	Broadcast	0.34	2.08	2.21	45.0	53640
5	Broadcast	0.35	2.10	1.87	39.0	50052
6	Dribble surface band	0.36	1.99	1.85	45.6	47541
7	Dribble surface band	0.34	2.03	2.47	50.8	52743
8	Dribble surface band	0.36	2.12	2.34	48.6	50949
9	Dual placement	0.34	2.14	1.37	28.9	58125
10	Dual placement	0.33	2.21	2.42	50.6	53641
11	Dual placement	0.33	2.24	1.59	35.5	53102
P-value		0.0078	0.0043	0.20	0.435	0.1918
MSE		0.001	0.010	0.468	0.000	7617.054
SED		0.026	0.082	0.559	0.000	6219
CV, %		6.521	4.794	35.740	36.381	14.893
Contrasts ^{I}		P-value				
1 vs 2		0.991	0.034	0.323	0.225	0.6292
3,4,5 vs 6,7,8		0.603	0.501	0.148	0.146	0.4334
3,4,5 vs 9,10,11		0.312	0.070	0.772	0.683	0.5334
6,7,8 vs 9,10,11		0.133	0.017	0.244	0.292	0.2202

3 vs 4	0.783	0.639	0.083	0.125	0.9093
3 vs 5	0.681	0.844	0.210	0.257	0.4967
4 vs 5	0.494	0.757	0.552	0.627	0.5704
6 vs 7	0.165	0.944	0.285	0.524	0.4128
6 vs 8	0.757	0.421	0.390	0.632	0.5897
7 vs 8	0.273	0.325	0.826	0.856	0.776
9 vs 10	0.516	0.444	0.092	0.106	0.4792
9 vs 11	0.601	0.272	0.695	0.589	0.4288
10 vs 11	0.897	0.730	0.171	0.240	0.9319

[I] Indicates the treatments being contrasted. SED – standard error of the difference between two equally replicated means, MSE- Mean square error, CV- Coefficient of variation (%)

Table 1.7. NDVI, grain N, grain yield, and N-uptake at EFAW site in 2019.

Treatment	Application method	NDVI	Grain N %	Grain yield Mg ha^{-1}	N-uptake kg ha^{-1}
1	No	0.77	1.48	2.89	42.7
2	Broadcast	0.76	1.53	3.20	49.4
3	Broadcast	0.75	1.46	3.67	53.5
4	Broadcast	0.73	1.63	4.16	67.5
5	Broadcast	0.76	1.69	3.98	67.8
6	Dribble surface band	0.77	1.38	3.42	48.1
7	Dribble surface band	0.74	1.49	4.07	60.6
8	Dribble surface band	0.76	1.36	3.64	49.3

9	Dual placement	0.74	1.89	3.68	69.0
10	Dual placement	0.74	1.59	3.40	53.4
11	Dual placement	0.77	1.36	3.65	49.0
P-value		0.904	0.003	0.405	0.069
MSE		0.003	0.024	0.437	0.000
SED		0.045	0.126	0.540	0.000
CV, %		7.764	10.151	18.295	20.847
Contrasts [I]		P-value			
1 vs 2		0.829	0.683	0.572	0.488
3,4,5 vs 6,7,8		0.624	0.023	0.475	0.076
3,4,5 vs 9,10,11		0.869	0.796	0.262	0.303
6,7,8 vs 9,10,11		0.745	0.013	0.675	0.424
3 vs 4		0.668	0.187	0.378	0.154
3 vs 5		0.856	0.077	0.572	0.144
4 vs 5		0.543	0.623	0.747	0.971
6 vs 7		0.569	0.377	0.243	0.201
6 vs 8		0.877	0.895	0.681	0.899
7 vs 8		0.678	0.312	0.440	0.246
9 vs 10		0.977	0.027	0.608	0.115
9 vs 11		0.491	0.001	0.954	0.047
10 vs 11		0.474	0.087	0.648	0.644

[I] Indicates the treatments being contrasted. SED – standard error of the difference between two equally replicated means, MSE- Mean square error, CV- Coefficient of variation (%)

Table 1.8. NDVI, number of heads, grain N, grain yield, and N-uptake at LCB 2019.

Treatment	Application method	NDVI	Heads ha^{-1}	Grain N %	Grain yield Mg ha^{-1}	N-uptake kg ha^{-1}
1	No	0.50	41620	1.30	2.26	30.6
2	Broadcast	0.44	31574	1.41	3.29	46.6
3	Broadcast	0.65	43414	1.30	3.32	43.3
4	Broadcast	0.54	35521	1.28	4.19	53.4
5	Broadcast	0.64	31216	1.30	3.57	46.8
6	Dribble surface band	0.59	38750	1.27	3.66	46.7
7	Dribble surface band	0.54	40903	1.25	3.50	43.8
8	Dribble surface band	0.56	43773	1.18	3.62	42.6
9	Dual placement	0.58	48437	1.43	4.56	65.3
10	Dual placement	0.52	40903	1.28	4.53	58.4
11	Dual placement	0.52	36597	1.36	4.20	56.9
P-value		0.319	0.842	0.51	0.011	0.059
MSE		0.008	122410844.000	0.014	0.345	0.000
SED		0.231	9033.67	0.097	0.480	0.000
CV, %		15.771	28.126	9.145	15.881	20.901
Contrasts [I]				P-value		
1 $2		0.379	0.279	0.259	0.045	0.068
3,4,5 vs 6,7,8		0.262	0.406	0.319	0.726	0.478
3,4,5 vs 9,10,11		0.097	0.325	0.252	0.015	0.018
6,7,8 vs 9,10,11		0.563	0.874	0.039	0.007	0.004

3 vs 5	0.164	0.393	0.808	0.088	0.240
3 vs 4	0.915	0.192	0.981	0.616	0.680
4 vs 5	0.196	0.639	0.790	0.214	0.438
6 vs 7	0.450	0.814	0.813	0.741	0.723
6 vs 8	0.645	0.584	0.351	0.932	0.624
7 vs 8	0.764	0.754	0.483	0.806	0.892
9 vs 10	0.379	0.414	0.144	0.960	0.420
9 vs 11	0.360	0.205	0.481	0.460	0.323
10 vs 11	0.970	0.639	0.431	0.490	0.852

[I] Indicates the treatments being contrasted. SED – standard error of the difference between two equally replicated means, MSE- Mean square error, CV- Coefficient of variation (%)

Table 1.9. NDVI, heads, grain N, grain yield, and N-uptake at EFAW in 2020

Treatment	Application method	NDVI	Heads ha^{-1}	Grain N %	Grain yield Mg ha^{-1}	N-uptake kg ha^{-1}
1	No	0.71	43773	1.28	5.31	68.7
2	Broadcast	0.77	59919	1.40	5.81	83.8
3	Broadcast	0.78	65301	1.34	5.29	72.7
4	Broadcast	0.81	71759	1.35	5.51	74.6
5	Broadcast	0.80	68889	1.51	5.92	88.7
6	Dribble surface band	0.70	56331	1.62	4.36	69.0
7	Dribble surface band	0.80	64583	1.26	5.43	68.9
8	Dribble surface band	0.82	58125	1.32	5.47	72.3
9	Dual placement	0.74	67813	1.44	7.08	102.3

10	Dual placement	0.78	66378	1.40	8.28	116.8
11	Dual placement	0.81	69607	1.36	5.43	71.1
P-value		0.093	0.002	0.073	0.475	0.489
MSE		0.002	73511645	0.014	5.281	0.001
SED		0.037	7000	0.097	1.876	0.026
CV, %		6.378	13.620	8.553	39.567	42.598
Contrasts [I]				P-value		
1 vs 2		0.145	0.032	0.227	0.794	0.597
3,4,5 vs 6,7,8		0.284	0.038	0.983	0.658	0.768
3,4,5 vs 9,10,11		0.334	0.861	0.992	0.225	0.221
6,7,8 vs 9,10,11		0.913	0.055	0.991	0.104	0.118
3 vs 4		0.427	0.367	0.885	0.906	0.702
3 vs 5		0.567	0.614	0.130	0.739	0.415
4 vs 5		0.822	0.686	0.122	0.830	0.621
6 vs 7		0.020	0.252	0.001	0.576	0.996
6 vs 8		0.006	0.800	0.006	0.560	0.910
7 vs 8		0.578	0.367	0.512	0.981	0.906
9 vs 10		0.317	0.840	0.751	0.532	0.615
9 vs 11		0.076	0.800	0.440	0.388	0.281
10 vs 11		0.407	0.650	0.646	0.145	0.122

[I] Indicates the treatments being contrasted. SED – standard error of the difference between two equally replicated means, MSE- Mean square error, CV- Coefficient of variation (%)

Table 1.10.NDVI, heads, grain N, grain yield and N-uptake at LCB in 2020

Treatment	Application method	NDVI	Heads ha^{-1}	Grain N %	Grain yield Mg ha^{-1}	N-uptake kg ha^{-1}
1	No	0.66	45747	1.17	4.75	55.8
2	Broadcast	0.72	53820	1.40	6.88	95.2
3	Broadcast	0.69	56510	1.53	6.39	97.3
4	Broadcast	0.71	62610	1.57	7.36	115.9
5	Broadcast	0.79	64584	1.64	6.24	95.9
6	Dribble surface band	0.74	55614	1.38	6.74	93.0
7	Dribble surface band	0.68	54896	1.42	5.29	73.3
8	Dribble surface band	0.69	49335	1.55	5.46	79.3
9	Dual placement	0.67	53640	1.55	6.39	99.4
10	Dual placement	0.70	57587	1.51	5.16	77.2
11	Dual placement	0.64	52205	1.43	5.32	76.5
P-value		0.018	0.006	0.000	0.211	0.164
MSE		0.004	21453667	0.007	1.843	0.000
SED		0.052	3782	0.068	1.108	0.000
CV, %		8.936	8.400	5.866	22.637	24.588
Contrasts [I]						
1 vs 2		0.296	0.045	0.005	0.070	0.037
3,4,5 vs 6,7,8		0.365	0.002	0.007	0.207	0.068
3,4,5 vs 9,10,11		0.062	0.006	0.081	0.120	0.074
6,7,8 vs 9,10,11		0.306	0.590	0.219	0.752	0.917
3 vs 5		0.800	0.123	0.540	0.392	0.301

3 vs 4	0.080	0.045	0.272	0.893	0.891
4 vs 5	0.128	0.608	0.569	0.324	0.432
6 vs 7	0.216	0.851	0.568	0.206	0.274
6 vs 8	0.292	0.113	0.096	0.264	0.634
7 vs 8	0.847	0.157	0.230	0.877	0.614
9 vs 10	0.495	0.309	0.600	0.281	0.222
9 vs 11	0.609	0.708	0.131	0.343	0.208
10 vs 11	0.239	0.170	0.309	0.893	0.968

[I] Indicates the treatments being contrasted. SED – standard error of the difference between two equally replicated means, MSE- Mean square error, CV- Coefficient of variation (%)

Table 1.11. Rainfall and temperature data throughout the growing season

	Rainfall (mm)			Temperature(° C)		
Month	2018	2019	2020	2018	2019	2020
Stillwater						
April	52.3	134.4	30.2	12.3	16.2	16.0
May	98.6	439.4	87.4	24	19.6	19.1
June	151.6	106.9	66	26.8	24.4	26.2
July	79.25	19.3	116.8	27.8	27.4	27.6
August	142	209.8	47.2	26.2	27.2	25.6
Sept	79.8	165.4	57.9	23.1	26.4	
LCB						
April		111	20.8	15.7	16.8	16.1
May		413.5	62.2	19.2	19.2	18.8

June	102.6	57.9	24.1	24.1	26.1
July	33.3	152.7	26.9	26.9	27.3
August	208	51.8	27.0	27.0	25.0
September	163.6	49	25.8	25.6	

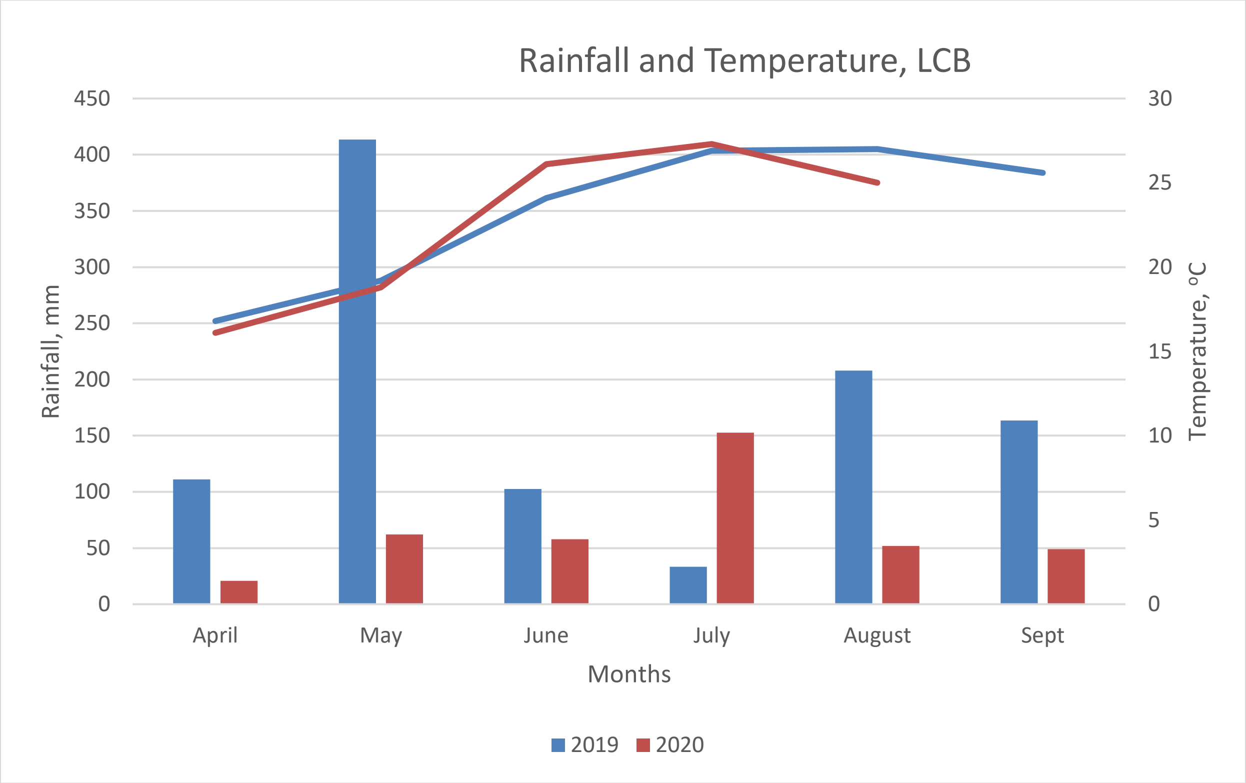

Figure 1.1. Monthly rainfall averages and temperature for LCB site

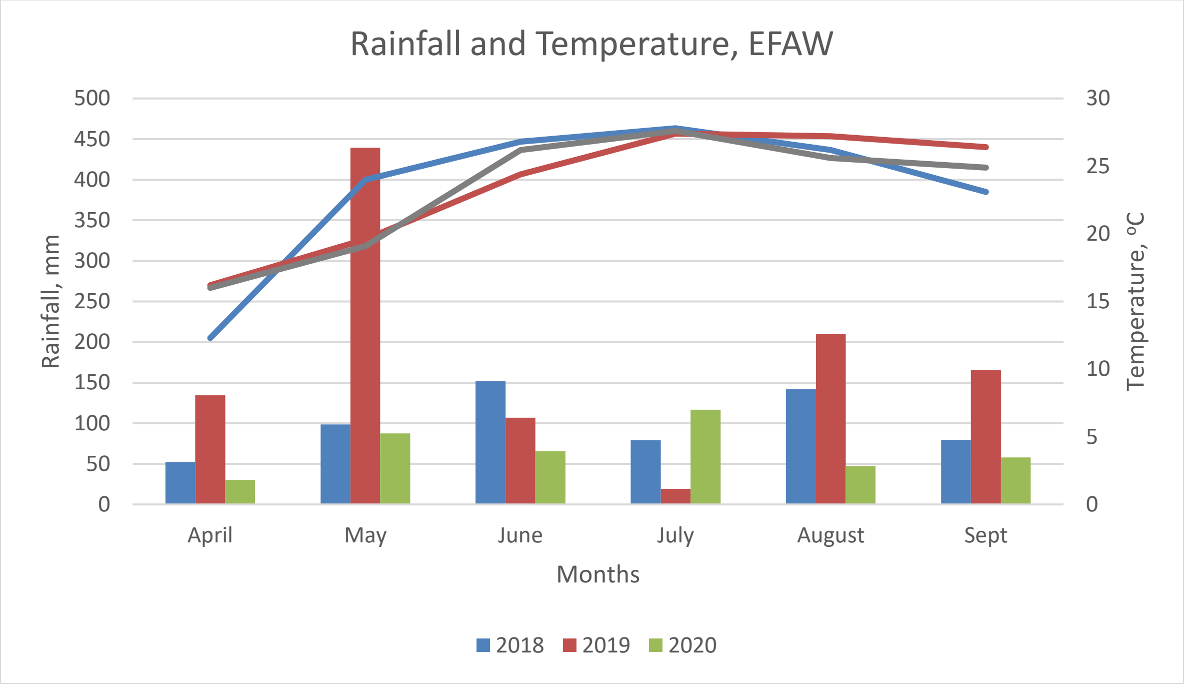

Figure 1.2. Monthly rainfall averages and temperature at the EFAW site

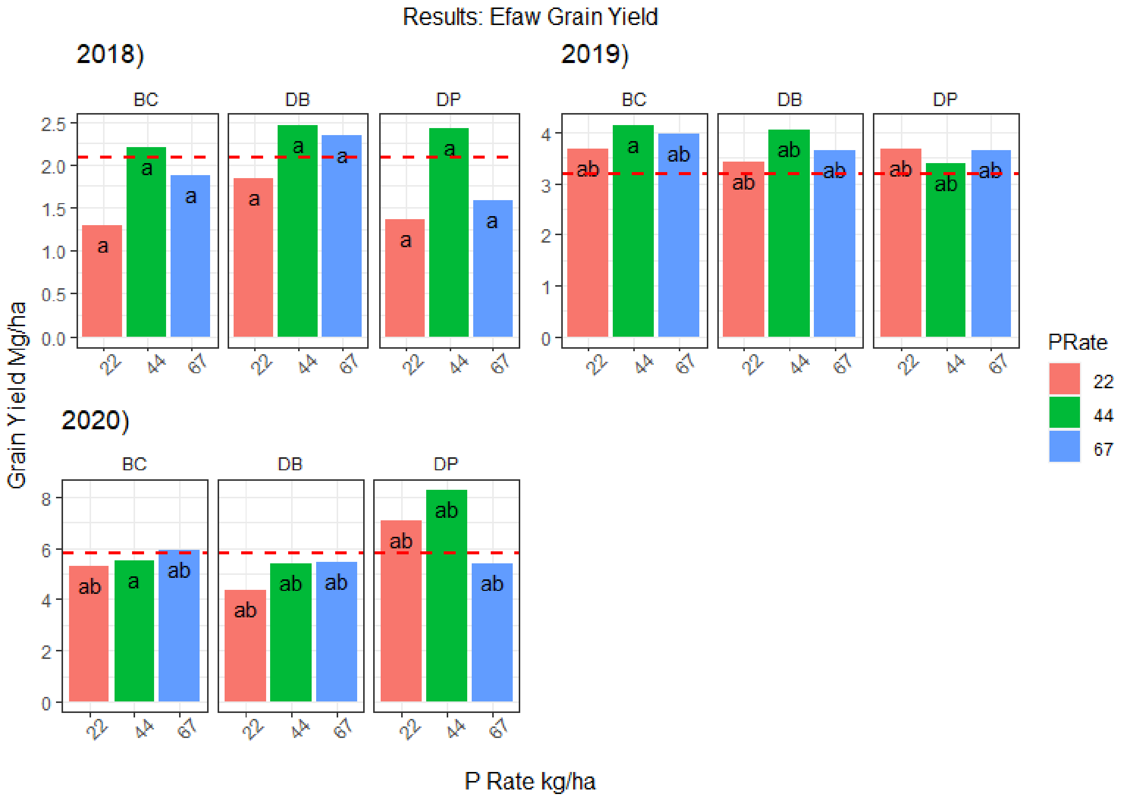

Figure 1.2. Grain yield at the EFAW site and the red line indicates the P-check

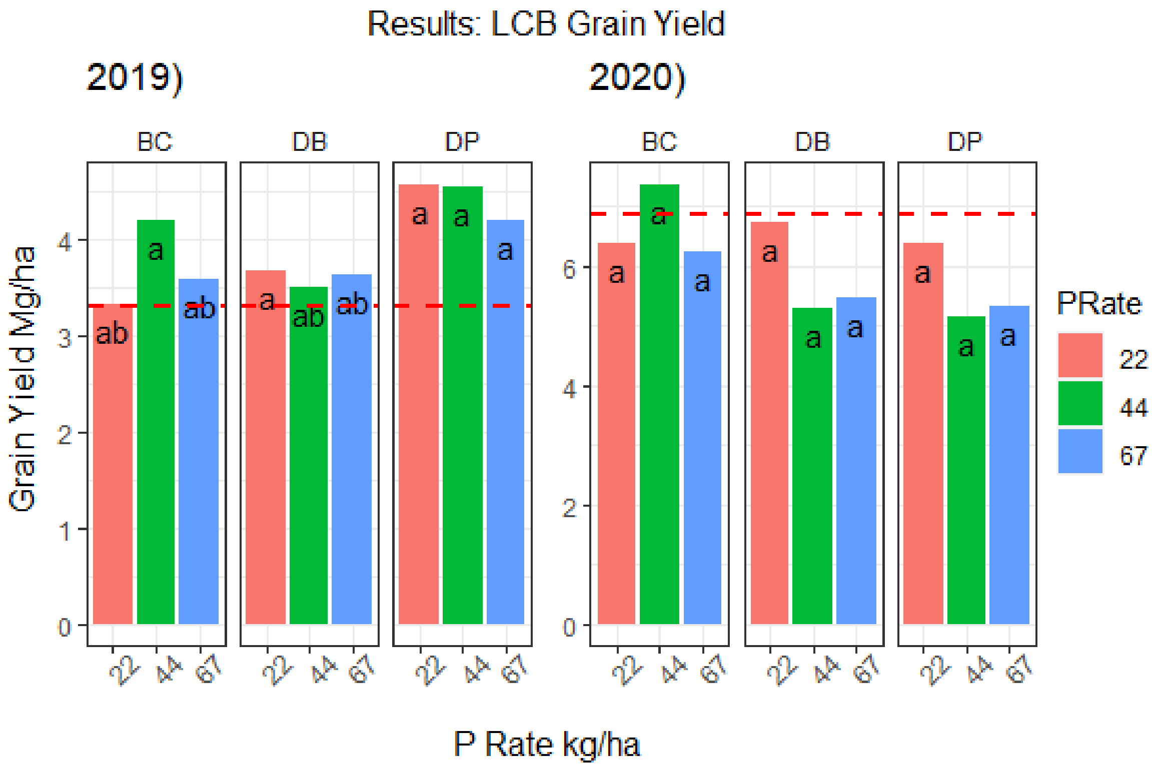

Figure 1.3. Grain yield at the LCB site and the red line indicates the P-check

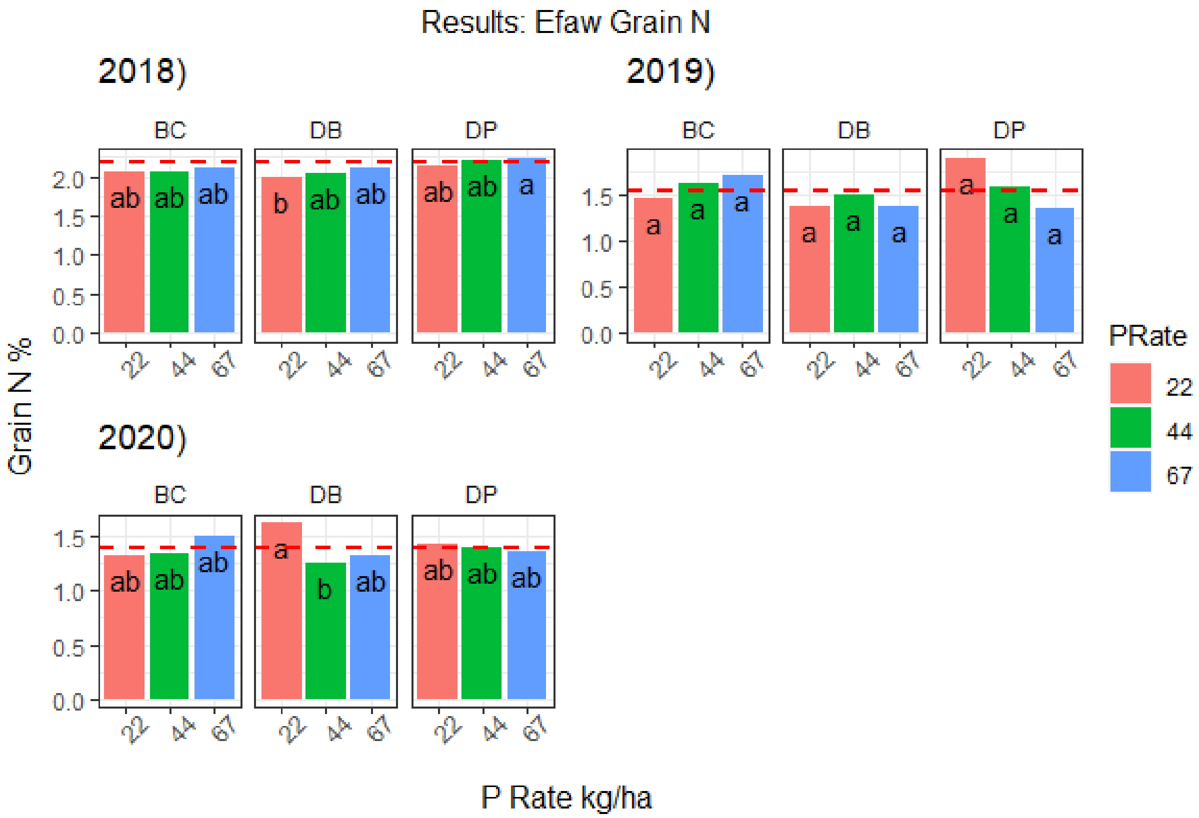

Figure 1.4. Grain N at the EFAW site and the red line indicates the P-check

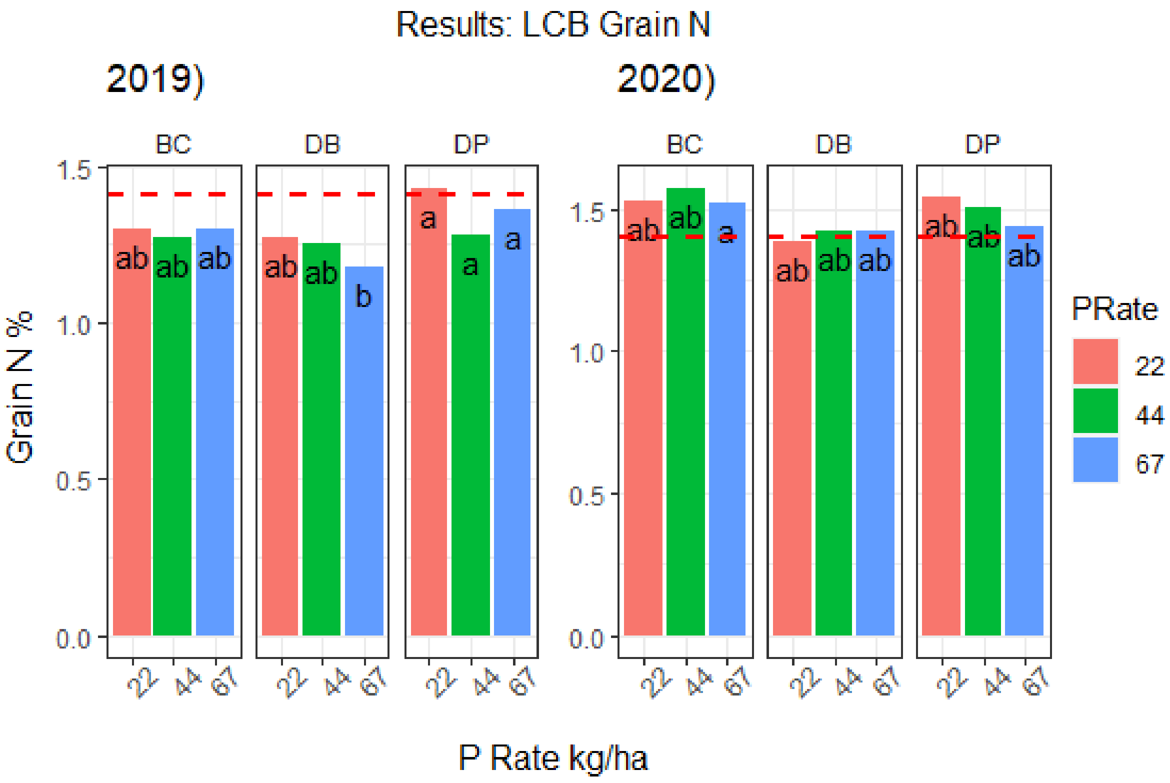

Figure 1.5. Grain N at LCB site and the red line indicates the P-check

Figure 1.6: Picture showing differences in heading at EFAW site

Figure 1.7: Picture showing differences leaf color of treatments at EFAW

CHAPTER II

USE OF NDVI READINGS FOR DETECTING EARLY-SEASON CHANGES IN PLANT BIOMASS AND POTENTIAL NITROGEN RESPONSE

Abstract

Producers are concerned with knowing the exact stage at which they should apply mid-season fertilizers to minimize yield loss and stand damage from equipment. Knowing optimum nitrogen (N) as early in the season as possible allows producers more time to make management decisions and apply needed nutrients. Normalized Difference Vegetative Index (NDVI) readings have been used successfully to predict yield potential and the N requirement of winter wheat. However early-season biomass production may be minimal resulting in low NDVI values which may be incapable of detecting difference in plant biomass. For this study, NDVI values were collected from three long-term field experiments in Oklahoma. Sensing was initiated early in the fall and carried through the spring (mid-March). Date of sensing and growing degree days (GDD>0) were recorded while the coefficient of variation (CV) was computed from NDVI readings. The values of NDVI versus GDD > 0, and CV versus GDD > 0 were graphically presented.

The general trend showed that NDVI values were low initially with limited difference between all of the treatments for the first 40 to 60 GDD>0 in four out of five site years. At 70 GDD > 0, there was a clear separation between treatments that signified difference in growth due to different nitrogen demands. The CV was high initially when NDVI values were low because there were large patches of bare soil due to limited growth, but later on CV increased when the canopy closed due to increased biomass. Grain yield was observed to increase with N rate. In general, differences in NDVI were detected as early as 70 GDD > 0. At this time, producers can start to prepare make decisions for fertilizing their crop.

2.1. Introduction

Nitrogen is a limiting nutrient in crop production and has the potential to increase profitability under appropriate management conditions (Teal et al., 2006). Raun et al. (2002) accounted for different fertilizer nitrogen (N) losses, which included loss via denitrification, which was accounted for at 9.5% in winter wheat (Triticum *aestivum*). According to work conducted by (Gauer et al. (1992) in which they evaluated effects of N fertilization on grain protein content. The authors noted increasing N supply was found to increase protein and N uptake but reduced nitrogen use efficiency (NUE).

Avoiding over-application of N fertilizers in crop production is one way to increase NUE and application methods that avoid applying large amounts of N can increase NUE (Mullen et al., 2003). Johnson and Raun (2003) also mentioned that N management strategies that increase NUE might only be possible to evaluate for the site–years when response index (RI) is greater than one. At the lowest N rates, it has been reported that NUE increases for each rate as RI increases because N inputs are less likely to be excessive (Johnson and Raun, 2003).

Johnson and Raun (2003) noted that part of the reason for the low NUE values was excess N present in the soil-plant system and the extent to which N is present in excess. Excess N can be determined by the potential yield and how much of that yield will be supported by non-fertilizer sources and most likely mineralized from soil organic matter. Previously, N application rates were based on grain yield goals determined from a recent 5-yr crop yield average and increased typically by 10 to 30% to assure adequate N for above-average growing conditions (Teal et al., 2006). According to Raun and Johnson (1999), in-season applied N resulted in more efficient fertilizer use in 4 of 5 yr. compared with N incorporated prior to planting winter wheat. Teal et al. (2006) recommended 33 kg N ha^{-1} should be applied for every Mg of wheat grain produced, and 20 kg N ha^{-1} for every Mg of corn (Zea Maize) grain. Mullen et al. (2003) reported the procedure used to arrive at the current Oklahoma recommendations and this was done using the equation, "N rec = yield goal (kg ha^{-1}) x 0.033", where the yield goal is based on the average wheat yield for the past 5 years, and where 33 kg of N is needed to produce 1000 kg of grain.

According to Raun et al. (2005), precision agriculture is a term that many farmers are using today to imply a more precise application of nutrients and pesticides. The NDVI index is calculated from crop reflectance in the near-infrared (NIR) (780 nm) and red (660 nm) wavelengths. The specific formula for NDVI follows, (NIR-Red)/(NIR+Red) where NIR and Red are reflectance measurements. This index is an excellent predictor of biomass and plant health (Moges et al., 2005). It was also reported by Freeman et al. (2007) that NDVI was found to be highly correlated with forage N uptake and grain yields of winter wheat. Moges et al. (2005) further reported that the reflectance measurements for predicting plant biomass and N uptake depend on the growth stage in several cereal crops.

Improved NUE by as much as 15% was found when N fertilization was based on an optically sensed in-season estimate of yield (INSEY) (Raun et al., 2002). Raun et al. (2005) reported that temporal influence on expressed variability and the exact resolution where agricultural technologies should be operated had not been agreed upon. Time of sensing was found to be critical when determining the potential yield of a crop (Raun et al., 2005).

According to a study by Dhillon et al. (2020), the optimum GDD > 0 needed to predict grain yield using NDVI to be between 97 and 112. Dhillon et al. (2020) went ahead to mention that using time and date to collect NDVI readings and predict yield potential can be beneficial in terms of formulating accurate midseason fertilizer N rates. Figueiredo et al. (2020) also found that there was an improvement grain yield prediction when NDVI was collected between 80 and 115 GDDs. Figueiredo et al. (2020) therefore concluded that these ranges can be used in future to collect sensor readings other than the old the mechanism which involved the use of Feekes stages.

Boman et al. (1995), reported that applying N in February and March resulted in plant tissue damage and lower forage yields due to less early-season growth than with other applications. Large (1954) thoroughly described the growth stages of wheat and showed the formation of tillers as early as Feekes stage 2 which possess challenges due to late mid-season N application and potential equipment i.e. tire track damage. Mullen et al. (2003) showed that all N can be injected pre-plant as anhydrous ammonia between mid-August and mid-September while still maximizing yields. The timing of N fertilizer application in winter wheat forage and grain production systems is an important management decision (Boman et al., 1995). This same work evaluated urea ammonium nitrate (UAN) that was applied at different growth stages (pre-plant, top dressed in December, January, February, and March). Results from this study revealed that N applied in February and March resulted in plant tissue damage and lower forage yields due to having less early-season growth than with other applications. Boman et al. (1995) also found that forage yield response (measured in late March to mid-April) to January and December N application was comparable to pre-plant incorporated N when adequate precipitation was received after N was applied. Whereas it is difficult to determine potential yield and calculate in season fertilizer rates based on NDVI early in the season, we are able to detect a change in biomass early in the season.

The objective of this study was to determine the value and significance of sequential, early season NDVI sensor readings in three long-term winter wheat experiments (Magruder, Exp. 222 and Exp. 502) and how these can be used to determine the difference in biomass early in the season for better fertilization decisions.

2.2. Materials and Methods.

Over two winter wheat crop cycles NDVI reflectance was collected with a GreenSeeker™ hand held sensor readings from three long term fertility trials in Oklahoma. The Magruder plots (1892), Exp. 222 (Stillwater, OK, established 1969), and Exp. 502 (Lahoma, OK, established 1970) were used to provide a wide range of grain yield values in effort test the hypothesis that early sensor based NDVI readings can be used to determine differences in plant biomass early in the season which in turn can be used to determine the timing of in-season fertilization.

For two field experiments Exp. 222 and Exp. 502 N, P, and K fertilizers were applied broadcast in the fall, before planting in all years. Pre-plant fertilizer sources were urea (N-P-K), (46–0–0), triple superphosphate (0–20–0), and potassium chloride (0–0–50). The Magruder plots have been described in detail in several publications (Dhillon et al., 2018; Girma et al., 2007). These articles have all included the Magruder Plots that have a total of 6 treatments, but that are unreplicated (established in 1892). Treatment 1 consists of manure applied every 4 years at a rate of 269 kg N ha-1, a check (no nutrients applied), N and P (67-15-0), N, P and K (67-15-28) and N, P and K plus lime (67-15-28 +Lime), all three values are in kg/ha (N, P, and K).

Exp. 222 and Exp. 502 employed randomized complete block experimental designs with four replications (Table2.1 &2.2) and both are further described by (Raun et al., 2017; Raun et al., 2011). Weed control followed the Oklahoma Agricultural Experiment Station protocol, and where different herbicides were used over this extended period.

The soil classification for Exp. 222 and the Magruder Plots is a Kirkland silt loam: fine, mixed, superactive, thermic Udertic Paleustoll. The soil for Exp. 502, is a Grant silt loam: fine-silty, mixed, superactive, thermic, Udic Argiustoll. The Lahoma Agricultural Experiment Station is 2 km west of Lahoma, OK, and is 130 km Northwest of Stillwater, OK. To complete this study, a few treatments were selected from all the three different locations based on the variation in N rates. Selected treatments are as follows: Exp. 222, treatment 1-4 with N rates (0-29-37, 45-29-37, 90-29-37, 135-29-37), Exp. 502 treatments 1-6 with N rates (0-20-56, 22-20-56, 45-20-56, 65-20-56, 90-20-56, 112-20-56) and lastly Magruder check, NP (67-15-28), NPK (67-15-28), NPKL (67-15-28+lime).

The collection NDVI readings was initiated shortly after germination in the fall and taken at regular intervals until the spring. Data were collected over the 2017-2018 and 2018-2019 cropping seasons from these three long term trials. Plots of NDVI vs GDD > 0, were made and by treatment and used to assess differences in plant biomass.

Tabulated experiment station records (Oklahoma Agricultural Experiment Station) is included, and digitized data from the Oklahoma Mesonet (Oklahoma Mesonet, 2018) was used to obtain GDD. To count as one day where growth was possible, or where GDD>0, the following condition in equation 1 had to be met

GDD = (((Tmin + Tmax)/2 – 4.4C) >0). [equation 1]

The NDVI data collected was analyzed using the GLIMMIX procedure in SAS 9.4 (SAS Institute, Cary, NC, USA), and treatment averages were compared using the LSD mean separation procedure at alpha of 0.05.

2.3. Results and Discussion

2017-2018 season

Average NDVI values for each treatment versus growing degree days (GDDs) were plotted and presented in (Figure 2.1). For Exp. 502, all 4 treatments followed a similar trend in the first 60 GDDs although they were significantly different. On average, NDVI values increased from about 0.30 at 43 GDDs to 0.35 at 53 GDDs. Within the same range of GDDs, average NDVI values for treatment 5, 6 and 7 were lower than those of treatments 1, 2 and 3 by 13%. This indicates that these treatment NDVI values were not only separated from the rest but also from each other (Figure 2.1). This limited difference in NDVI readings was expected as there is limited growth that take place due periodic winter freezing on winter wheat early in the season from the 12/5th to 12/ 8th 2017. However, at 65 GDDs, NDVI readings decreased gradually for all treatments and these were inconsistent up to about 70 GDDs before later seeing a gradual increase in NDVI values which is quite unstable. At this stage, differences in plant biomass were observed. At 65 GDDs, treatment separation was observed. Nonetheless, NDVI values remained very low, below 0.5 for the first 92 GDDs and only reached 0.5 at two instances at 97 GDDs for treatments 3 and 4. This increase is consistent with work by Sembiring et al. (2000) that documented NDVI as a good predictor of plant biomass. However, this cannot be conclusive since we continued to see a couple of freezing days that indicated limited growth until late February (02/24/2017). Also, something to note at this location is that NDVI values for treatments with the highest N rates was low initially and only picked up at 80 GDD. This lag in values was associated with the buildup of crop residue due to the very high nitrogen rates.

The relationship between CV for the different NDVI readings and GDDs was also presented in Table 4. In general, CV was really inconsistent due to the non-uniform growth that occurs during the early stage of winter wheat caused by weather fluctuations and also wide variations in growth. For the first 69 GDDs, the highest CV registered was about 19.01% for treatment 2and 5 however, after that, CV decreased gradually up to 97 GDDs. For this particular treatment, The CV was high initially before later declining. This meant that the decrease in NDVI at 65 and 69 GDDs was accompanied by an increase in biomass variability. In general, CV was high initially but declined with increased temperatures and resultant growth and improved canopy cover. However, this did not occur until 78 GDD. This was supported by research done by Raun et al. (2005) in corn that found increased growth as CV decreased. Treatment 4 had the highest average NDVI value (0.52), while treatment 6 had the lowest with a mean NDVI value of 0.26, which practically would show the highest NDVI, given the high pre-plant N rate (112 kg N ha^{-1}) but this was not the case a lot of this may have to with environment (Dhital and Raun, 2016) discussed why variability could occur in which some of the treatments with no N applied yielded the same or even better than the N treated plots. This was further explained by (Mamo et al., 2003) in a study where some of the treatments did not respond to an N application due to spatial variability and lack of mineralization of organic N.

For Exp. 222, all 4 treatments followed the same trend for the first 36 GDDs NDVI readings were not significantly different (p value > 0.05) for the all the treatments (Figure 2.2). For the first 36 GDDs, The NDVI values were very low (mostly 0.2 and below) with limited differences between treatments. At 48 GDDs, differences started to emerge between treatment NDVI readings showing a gradual increase. This was particularly prominent between treatments receiving less than 90 kg N ha^{-1} and those receiving at least 90 kg N ha^{-1}. A more gradual changes were apparent up to 60 GDDs. Beyond 60 GDDs, variation was more evident. At 69 GDDs, an observed sudden decrease in NDVI was evident, suggesting that a corresponding change in biomass was present. This change may have possibly been brought about by the very low freezing temperatures experienced between 12/21/2017 and 01/18/2017. The NDVI values for treatments 3 and 4 followed a similar trend in most of the GDDs considered in this study. These treatments had NDVI values which were widely separated from treatments 1 and 2. On average, treatment 1 and 2 resulted in a 6.7% higher NDVI values than treatments 3 and 4 for the first 70 GDDs. Similar to Exp. 502, NDVI values were lower for treatments that received large quantities of N. However, after 70 GDDs treatment 4 surpassed all the other treatments contrary to Exp. 502.

The computed CVs coming from NDVI readings in Exp. 222 are reported in Table 5. Generally, CV was high initially when NDVI readings were first collected. The high cv must have been due to the wide variation within the treatments cause by weeds at the time of planting and other environmental factors as discussed by Dhital and Raun (2016). However, at 58 to 86 GDD, we start to observe an increase in variation followed by a decline at 103GDD and beyond. This is an indication that after herbicide application and weeds die, we attain back the normal trend which depicts a high CV in the initial stage of growth and low as high biomass accumulates late in the season. This also implied that there was a significant visible change in plant biomass at this at 80 GDDs. A similar response was demonstrated by Martin et al. (2007), where they studied the progression of NDVI during the life cycle of corn. Results coming from Exp. 222 indicate that treatment 4 had the highest NDVI; while treatment 3 had the lowest at about 110 GDDs. Treatment 3 and 4 received 90 and 135 kg N ha^{-1}, respectively. Part of the reason the low values of NDVI could possibly be due to the availability of more N than what was needed, and this potentially diminished growth (Raun and Johnson, 1999).

Results from the Magruder Plots are similar to what was observed at Exp. 222. For the first 40 GDDs, all four graphs representing the different treatments were close together implying that there was limited change in plant biomass. Very near to 50 GDDs, gradual differences began to appear, and that progressed up to 70 growing degree-days (Figure 2.3). After that, all treatments had a clear difference in plant biomass, showing a peak between 87 and 120 GDDs for all treatments with an average NDVI of 0.38. Within these GDDs, average NDVI was highest for NPKL (0.53) and lowest in the unfertilized check plot (0.25). This is supported by work coming from Martin et al. (2007), that showed a direct correlation between NDVI and plant biomass. In this study, NDVI values for the first 74 GDDs, NDVI values for all treatments averaged approximately 0.21, a figure close to 0.19 in the unfertilized check plot. The most salient observation coming from the Magruder Plots was that NDVI values in the check plot (no nutrients applied since the trial began in 1892) were mostly the same when compared to the other treatments receiving combinations of one or more of N, P, K, and lime up until 80 GDD. This, in turn, indicates when exactly one should expect to see differences based on cumulative GDDs in another environment and/or year. This is similar to what was discovered by Girma et al. (2008) while trying to untangle the puzzle in which they found the check plot to give yields > 1 Mg ha^{-1}, a factor that was attributed to improved genetics. The NPK +lime treatment showed greater NDVI values after 70 GDDs, possibly because of the lime, which was added and that influenced plant growth via soil pH regulation. This was further discussed by Dhillon, Del Corso et al. (2018) where he mentioned that lime plays a role in increased nutrient availability to the crop and decreases aluminum activity as well. Davis et al. (2003) mentioned that there is an N addition of 44.5 kg N ha^{-1} yr^{-1} due to N in the rain and N via symbiotic N fixation.

2018-2019 season

At Exp.502, results from this location were similar to what was observed at Exp.222 and Magruder in 2017-2018 growing season. For the first 40 GDDs, NDVI readings were mostly close for all the treatments (values below 0.3). From 40 GDDs, values stated to increase mostly for all the treatments reaching 0.4 on average around 01/21/2019 which was later followed by a small decline at 60 GDDs. The decline must have been associated with the very low temperatures experienced between 01/21 and 01/25/2019. The highest NDVI values started increasing starting at 70 GDDs and by 100 GDDs, the separation between the treatments is very evident. Therefore at 70 GDDs, the difference in biomass is evident for all the treatments and with little wait to 100 GDDs, yield can be predicted and fertilizer recommendations can be made. Looking at the individual treatments, they depict the expected trend where treatment 6 with the highest N rate had its curve on top followed by 5, 4, 3, 2 and 1 respectively. Looking at CV, The values are inconsistent where they did not agree completely to the trend in NDVI readings. This could suggest that there were wide variations within the experiment early in the season. These variations could have been caused by some patches growing faster than others due to residue and pre-plant N. This is in agreement with Taylor et al. (1999) where he mentioned that large coefficients of variation (> 30) can be an indication experimental variability. Taylor et al. (1999) found that using CV to compare variability among trials may not be proper and instead suggested the use of mean square errors.

Data coming from Exp. 22 indicates that there is a similar trend in NDVI as observed with all the other locations. For the first 45 GDDs, NDVI values were pretty low and ranged between 0.15 to 0.2. There was no clear separation amongst all the 4 treatments considered in this study. From 45 to 55 GDDs, there is a rapid increase in NDVI to 0.5, which is followed by a decline that is unstable for all the treatments. At around 75 GDDs, there is evidence for separation of all treatments which is an indication that they start to respond to the different fertilizer levels. By 80 GDDs, there’s clear evidence of accumulation in biomass. In general, the values of CV were inconsistent similar to what was observed at other locations. This is embedded within the wide variations within the data at the beginning of the season. Although the values still remain very high within the first 100 GDDs.

The trend in NDVI that was observed throughout all the site years with the exception of Exp. 502 (2017/2018) indicates that early in the season, NDVI readings are very low, however, after germination there's a very slight increase which is almost unnoticeable. However, between December and mid-February, it is almost impossible to see differences in treatments.

Growth and development of winter wheat is highly influenced by temperature and rainfall patterns (Bauer et al., 1984). The temperature pattern for winter wheat in Oklahoma is in such a way that temperatures are higher in October (at least 20ºC) but go on dropping and by January, where average temperatures have reached negatives (Figure 14). This is later followed by an increase back to positive values by mid-February. However, the most important feature to note about this pattern is that during the very cold period when temperatures are low, the crop undergoes a stage of dormancy. During this stage, there's limited growth and almost no change in biomass. This dormancy period usually also coincides with the limited amount of rainfall (Figure 2.13) and this greatly affects the crop. During this period, it is hard to differentiate the different treatments in terms of biomass.

In general, this study still suggests that collecting NDVI in winter wheat early in the season is still viable in terms of detecting where there is a sudden increase in biomass. From the results, it is clear that around 70 GDDs we start to experience an increase in growth. This is in agreement with work conducted by (Dhillon et al., 2020; Figueiredo et al., 2020). The authors that from 80 GDDs and beyond, producers can accurately predict yield and obtain appropriate fertilizer recommendations. Therefore, for a trial planted by 10/15, producers should look at starting to sense by the last week of February to be able to catch that variation within treatments and fertilizer decisions can be made early enough to avoid damaging the crop from trampling as was explained by Large(1954) and Miller (1999). This period also coincides with what most farmers refer to as the stage prior to the appearance of the hollow stem (Edwards and Horn, 2010). This is because just after a hollow stem appears the wheat starts to grow vigorously since the temperatures are also becoming warmer. Therefore, any delay in N application would damage the crop severely. Furthermore, Bigatao Souza (2018) found an increase in grain yield when N was applied approximately at 94 GDDs.

Grain yield averaged 1.89 and 3.13 Mg ha^{-1} in 2017-2018 and 2018-2019 at Lahoma respectively (Table2.9). These results indicate that the rainfall pattern had a significant impact on grain yield when you compare the two seasons. In 2017-2018, Lahoma received a total of 381.8 mm and in 2018-2019, a total of 961.1 mm rainfall was received (Figure 2.13). This difference could have impacted yield thus the huge difference in the two years. At the Stillwater site, grain yield averaged 2.86 in 2017-2018 and 1.68 Mg ha^{-1} in 2018-2019. In general, grain yield increased with N rate across sites. This is consistent with other research conducted in the long-term trials. Omara et al. (2020) found that N rate to account for 29 and 23% grain yield at Lahoma and Stillwater, respectively.

2.4. Conclusion

For four of the site years, NDVI plotted as a function of GDDs followed a similar trend where for approximately the first 40 GDDs, no significant changes in plant growth were observed. Beyond 40 GDDs detections of differences in biomass become more detectable, and that can, in turn, be used to predict potential yield and mid-season fertilizer N requirements. For Exp. 502, NDVI readings were inconstant for the first 60 GDDs, however, at 65 a decline was observed. It is almost impossible to determine changes in plant biomass early in the season given the number of freezing days that could deter growth. This work further suggests that the optimum time to decipher N needs is likely near 70 to 80 GDDs which is around early February and also when visual differences becomes more pronounced.

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Table 2. 12. Treatment structure for experiment 502.

TRT	Pre-plant N rate (kg Nha^{-1})	Pre-plant P rate (kg P ha^{-1})	Pre-plant K rate (kg K ha^{-1})
1*	0	0	0
2*	0	20	56
3*	22	20	56
4*	45	20	56
5*	67	20	56
6*	90	20	56
7*	112	20	56
8	67	0	56
9	67	10	56
10	67	29	56
11	67	39	56
12	67	29	0
13	112	39	56
14	67	20	56 (Sul-Po-Mag)

N applied as 46-0-0 (Urea)

P applied as 0-46-0 (Triple Super Phosphate)
K applied as 0-0-60 (Potash)
* - YP plot

Plot size: 16’ X 60’

Alley: 20’
Total trial area: 224’ X 300’

Treatment 2- 7 were used in this study because they had varying rates of N while P and K were constant.

Table 2. 13. Treatment structure for experiment 222

TRT	Pre-plant N rate (kg N ha^{-1})	Pre-plant P rate (kg P ha^{-1})	Pre-plant K rate (kg K ha^{-1})
1*	0	29	37
2*	45	29	37
3*	90	29	37
4*	135	29	37
5	90	0	37
6	90	15	37
7	90	44	37
8	90	29	0
9	90	29	75
10*	0	0	0
11	135	44	75
12	135	44	0
13	90	29	37 (Sul-Po-Mag)

N applied as 46-0-0 (Urea)
P applied as 0-46-0 (Triple Super Phosphate)
K applied as 0-0-60 (Potash)
* - YP plot
^ - Split 120 lb. N rates to 67.5 kg N (fall) and 667.5 kg N (spring)

Treatment 1 – 4 were used in this study because they had varying rates of N while P and K were constant.

Table 2.14. Treatments structure for the Magruder Plots.

Treatment no.	composition
1	manure every 4 years at 269kg Nha-1
2	Check- No nutrients applied
3	P 0-34-0
4	NP 67-15-28
5	NPK 67-15-28
6	NPKL 67-15-28 +Lime
* Lime applied when soil PH<5.5. (1929-1954)	
N Source: 46-0-0	Fertilizer Rates:
P Source: 0-46-0	67 kg N ha^{-1}
K Source: 0-0-62	15 kg P ha^{-1}
Lime: as required	28 kg K ha^{-1}

Treatment 3-6 were used in this study because they had varying rates of N

Table 2.15: Planting and Harvest dates for Exp. 502, 222 and Magruder Plots

	Exp.502		Exp.222	
Activity	2017/2018	2018/2019	2017/2018	2018/2019
Planting	10/13/2017	10/18/2018	10/10/2017	10/30/2018
Harvest	6/12/2018	6/22/2019	6/14/2018	6/14/2019
	Magruder			
Planting	10/19/2017			
Harvest	6/10/2018			

Table 2.16. Mean normalized difference vegetation index (NDVI) and coefficient of variation at different GDD > 0.

	NDVI and CVs for 6 treatments											
	1		2		3		4		5		6	
GDD	NDVI	Cv%	NDVI	Cv%	NDVI	Cv%	NDVI	Cv%	NDVI	Cv%	NDVI	Cv%
43	0.36	5.84	0.36	6.53	0.35	9.91	0.28	17.02	0.24	11.47	0.21	5.23
46	0.38	7.02	0.38	7.43	0.37	12.81	0.30	15.19	0.25	12.33	0.22	1.28
49	0.40	9.15	0.42	5.68	0.41	11.04	0.32	16.54	0.27	13.17	0.22	4.02
53	0.40	10.98	0.43	5.76	0.43	10.35	0.34	12.82	0.28	14.49	0.23	5.54
65	0.37	15.68	0.40	2.02	0.43	8.59	0.35	17.29	0.28	13.16	0.24	8.80
69	0.34	15.65	0.36	2.79	0.39	10.58	0.32	19.01	0.24	17.59	0.20	15.91
71	0.33	13.69	0.35	3.78	0.38	8.92	0.32	15.25	0.25	12.76	0.21	5.86
74	0.34	14.13	0.35	1.41	0.39	7.33	0.35	12.26	0.27	11.89	0.24	10.74
76	0.32	14	0.34	3.02	0.38	5.43	0.33	12.62	0.25	13.05	0.21	10.41
77	0.33	13.2	0.35	2.23	0.39	5.8	0.35	11.21	0.27	12.18	0.23	15.38
78	0.31	13.21	0.33	3.3	0.37	5.97	0.33	12.48	0.27	11.29	0.21	3.74
83	0.37	10.49	0.39	1.25	0.42	6.76	0.40	8.86	0.33	8.83	0.28	9.91
89	0.35	13.75	0.37	3.78	0.43	7.08	0.41	10.29	0.32	13.53	0.28	9.17
92	0.37	9.46	0.41	1.55	0.48	6.71	0.46	6.73	0.38	12.35	0.32	10.58
97	0.38	11.5	0.44	3.65	0.51	8.51	0.52	7.27	0.43	13.27	0.37	8.59

N rates for treatments 2-7 (0-20-56, 22-20-56, 45-20-56, 67-20-56, 90-20-56, 112-20-56) respectively at different GDDs at Lahoma, Ok, Exp. 502. 2017.

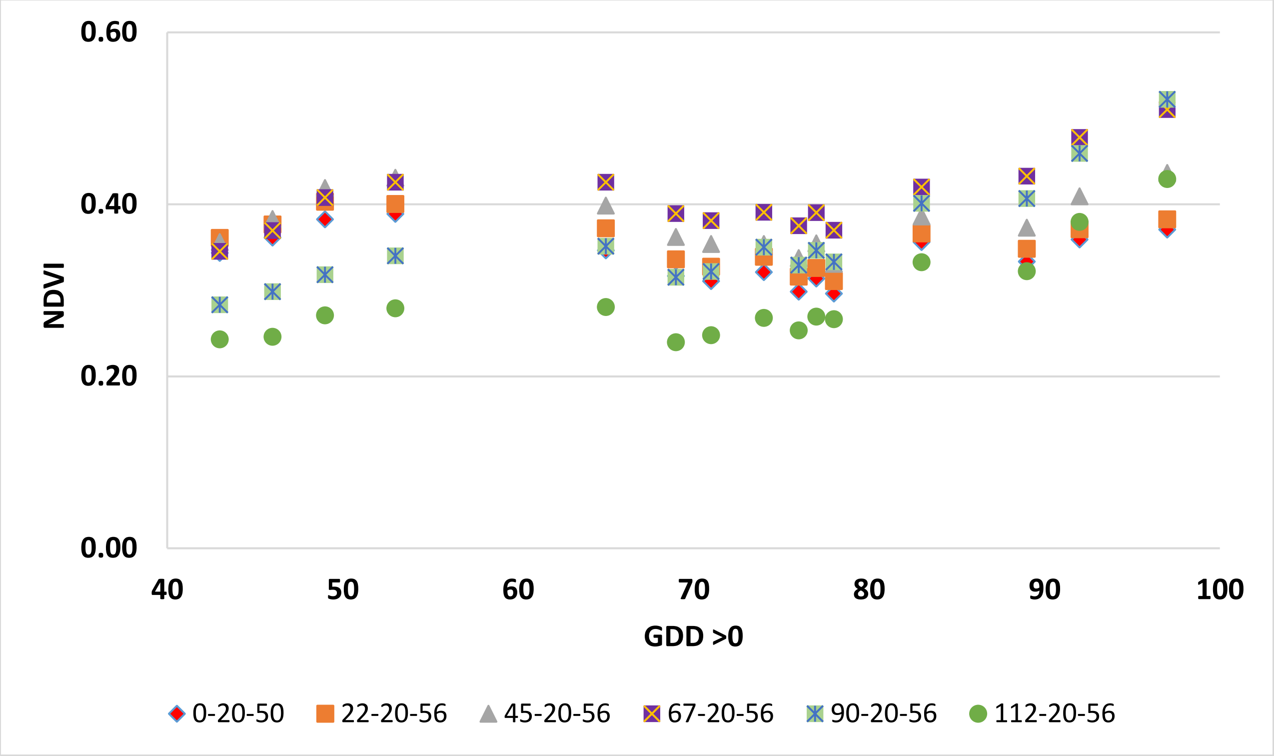

Figure 2.8. Normalized difference vegetative index (NDVI) readings collected from select treatments with in the E502 long term fertility trial in Lahoma, OK over the 2017-2018 growing season (Oct – June). The NDVI values are plotted by GDD > 0, which is a measure the counts any day with an average daily temperature of 4.4C .Treatments utilized for this study were 2 to 7, (0-20-56, 22-20-56, 45-20-56, 67-20-56, 90-20-56, 112-20-56).

Table2.17. Mean normalized difference vegetation index (NDVI) and coefficient of variation (CV) at different GDD > 0.

	Average NDVI and CV% for the 4 treatments							
GDD	1		2		3		4	
	NDVI	CV%	NDVI	CV%	NDVI	CV%	NDVI	CV%
16	0.15	26.1	0.15	20.6	0.15	15.8	0.15	15.3
27	0.2	20.6	0.2	19.6	0.19	14.2	0.21	12.8
30	0.19	21.6	0.19	20.5	0.2	11.8	0.2	12.3
36	0.2	14.2	0.19	18.6	0.2	10.4	0.2	11.7
44	0.22	8.3	0.21	17	0.19	7.9	0.18	15.7
48	0.24	8.7	0.22	16.1	0.21	9.8	0.21	10.5
54	0.24	8.1	0.23	15.9	0.21	9.8	0.21	8.8
58	0.23	7.5	0.21	16.3	0.21	9.7	0.22	6.7
62	0.25	7.5	0.24	16	0.22	8.4	0.2	9.2
64	0.26	6.6	0.26	14.1	0.24	6.9	0.25	6

67	0.27	6.9	0.26	13.8	0.23	6.4	0.22	5.9
69	0.25	6	0.22	12	0.22	4.8	0.23	5.5
71	0.25	5.1	0.24	9.3	0.22	4.7	0.26	5.5
73	0.3	4.9	0.29	8.7	0.27	7	0.32	5.3
86	0.35	4.8	0.35	6.7	0.4	3.5	0.35	5.5
93	0.45	4.6	0.42	7.1	0.43	2.9	0.52	5.2
103	0.53	4.1	0.49	6.7	0.44	2.7	0.57	4.8
110	0.61	2.8	0.57	2.6	0.51	1.8	0.63	4.2

N rate for treatments 1-4 (0-29-37, 45-29-37, 90-29-37, 135-29-37) respectively at Stillwater, OK Exp. 222, 2017.

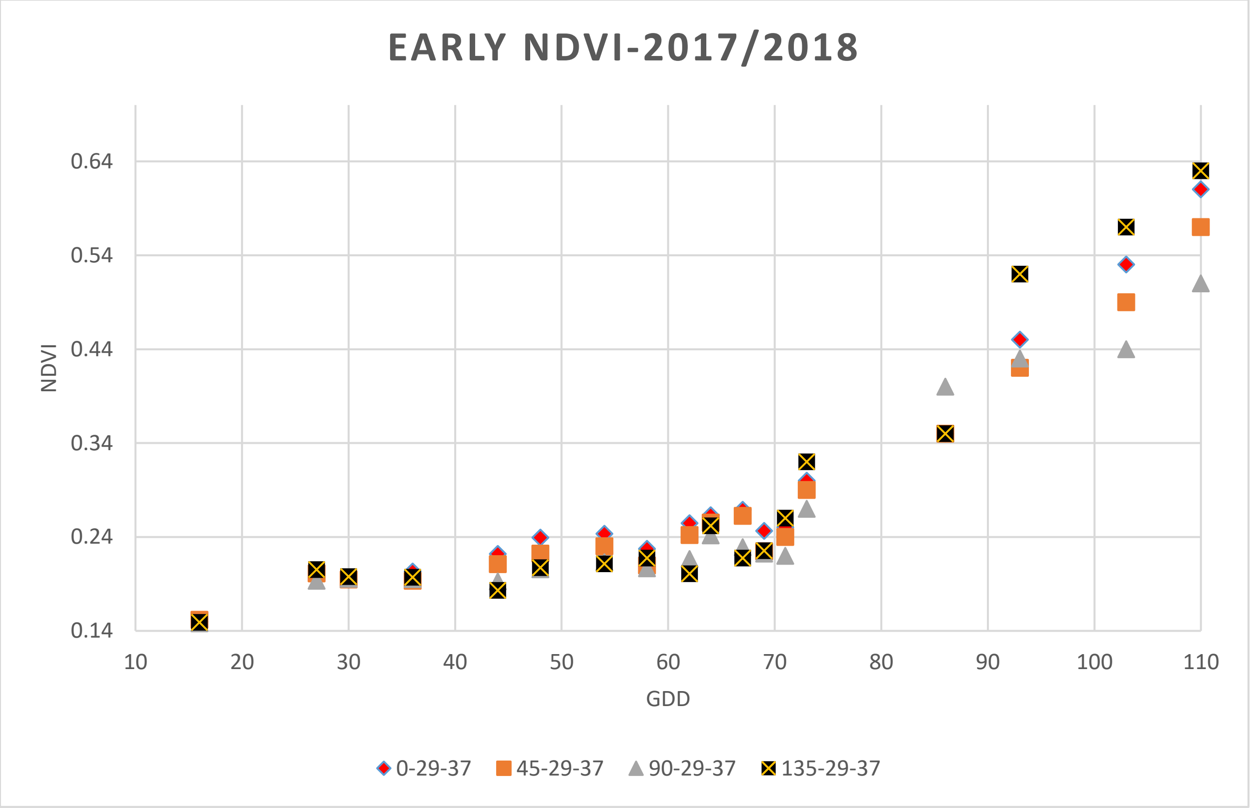

Figure 2.9. Normalized difference vegetative index (NDVI) readings collected from select treatments within the Exp. 222 long term fertility trial in Stillwater, OK over the 2017-2018 growing season (Oct – June). The NDVI values are plotted by GDD > 0, which is a measure the counts any day with an average daily temperature of 4.4C .Treatments utilized for this study were 1 to 4, (0-29-37, 45-29-37, 90-29-37, 135-29-37).

Table 2.18. Mean normalized difference vegetative index (NDVI) at different GDD>0 for Magruder Plots

	Mean NDVI for 4 treatments			
GDD	Check	NP	NPK	NPK+L
12	0.16	0.18	0.18	0.17
17	0.14	0.15	0.15	0.15
20	0.16	0.18	0.18	0.17
24	0.19	0.19	0.21	0.2
28	0.18	0.2	0.19	0.19
31	0.18	0.2	0.18	0.18
33	0.19	0.21	0.19	0.19
37	0.17	0.18	0.18	0.17
40	0.21	0.25	0.2	0.2
45	0.18	0.23	0.19	0.19
47	0.21	0.25	0.18	0.19
49	0.18	0.25	0.2	0.21
54	0.27	0.28	0.28	0.38
55	0.19	0.26	0.22	0.22
59	0.22	0.23	0.19	0.2
63	0.2	0.23	0.19	0.2
65	0.25	0.27	0.22	0.22
68	0.23	0.26	0.2	0.21
70	0.18	0.26	0.19	0.2
71	0.23	0.26	0.2	0.19
71	0.23	0.25	0.21	0.23
72	0.23	0.24	0.21	0.22
74	0.29	0.34	0.22	0.24
87	0.24	0.33	0.29	0.5
94	0.24	0.37	0.33	0.53
104	0.29	0.46	0.39	0.53
114	0.23	0.39	0.32	0.54
120	0.25	0.48	0.45	0.55

Average Normalized Difference Vegetation Index (NDVI) for the different treatments at different GDD >0

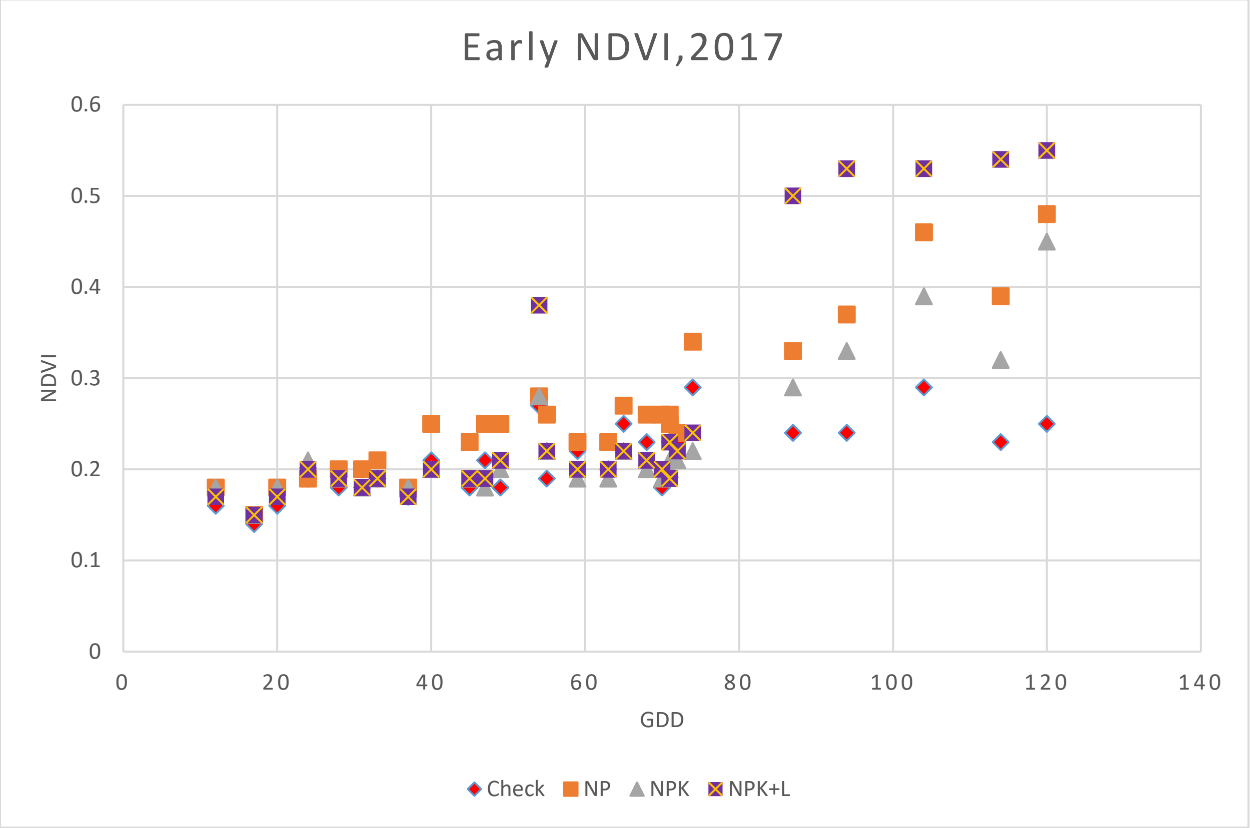

Figure 2.10. Normalized difference vegetative index (NDVI) readings collected from select treatments with in the Magruder Plots long term fertility trial in Stillwater, OK over the 2017-2018 growing season (Oct – June). The NDVI values are plotted by GDD > 0, which is a measure the counts any day with an average daily temperature of 4.4C .Treatments utilized for this study were (Check, NP, NPK and NPK + L).

Table 2.19: Mean normalized difference vegetative index (NDVI) and coefficient of variation (CV) at different GDD > 0

	NDVI and CVs for 6 treatments											
	1		2		3		4		5		6	
GDD	NDVI	Cv%	NDVI	Cv%	NDVI	Cv%	NDVI	Cv%	NDVI	Cv%	NDVI	Cv%
29	0.28	16.01	0.27	18.17	0.34	28.79	0.28	20.88	0.30	22.98	0.27	18.38
38	0.36	10.27	0.37	18.65	0.37	13.13	0.40	15.21	0.40	15.86	0.39	9.28
43	0.24	14.25	0.28	17.49	0.28	17.60	0.31	18.87	0.26	23.55	0.25	19.86

46	0.36	13.76	0.38	10.63	0.38	20.88	0.37	12.81	0.30	15.18	0.25	13.69
49	0.38	13.62	0.40	12.06	0.42	13.74	0.41	11.04	0.32	16.55	0.27	14.47
50	0.33	9.04	0.33	12.62	0.37	12.08	0.35	17.70	0.41	16.96	0.37	11.65
52	0.34	9.68	0.34	18.28	0.39	18.90	0.38	10.94	0.43	12.78	0.38	11.13
57	0.42	6.07	0.43	20.75	0.40	5.54	0.42	14.45	0.44	13.14	0.42	12.33
59	0.35	8.21	0.35	19.15	0.39	7.44	0.42	9.74	0.45	14.06	0.40	13.16
65	0.37	5.30	0.37	18.95	0.37	5.68	0.38	8.68	0.42	8.81	0.37	10.24
67	0.42	2.73	0.47	7.09	0.41	8.53	0.42	9.44	0.46	5.52	0.42	7.83
71	0.40	2.17	0.41	7.01	0.46	6.34	0.51	5.34	0.52	4.74	0.50	7.48
78	0.38	3.18	0.39	9.15	0.45	7.22	0.50	8.68	0.54	7.85	0.51	8.65
85	0.38	5.64	0.39	5.92	0.47	4.30	0.55	5.41	0.61	5.34	0.61	7.48
97	0.39	8.34	0.39	4.50	0.44	4.16	0.57	4.16	0.66	6.83	0.71	7.21
104	0.33	2.10	0.35	6.75	0.40	4.03	0.53	5.91	0.62	6.91	0.72	2.35
118	0.42	1.40	0.44	6.61	0.47	3.74	0.56	2.44	0.62	3.48	0.69	4.71

N rate for selected treatments 1-4 (0-29-37, 45-29-37, 90-29-37, 135-29-37) respectively at Stillwater, OK Exp.502, 2018 - 2019

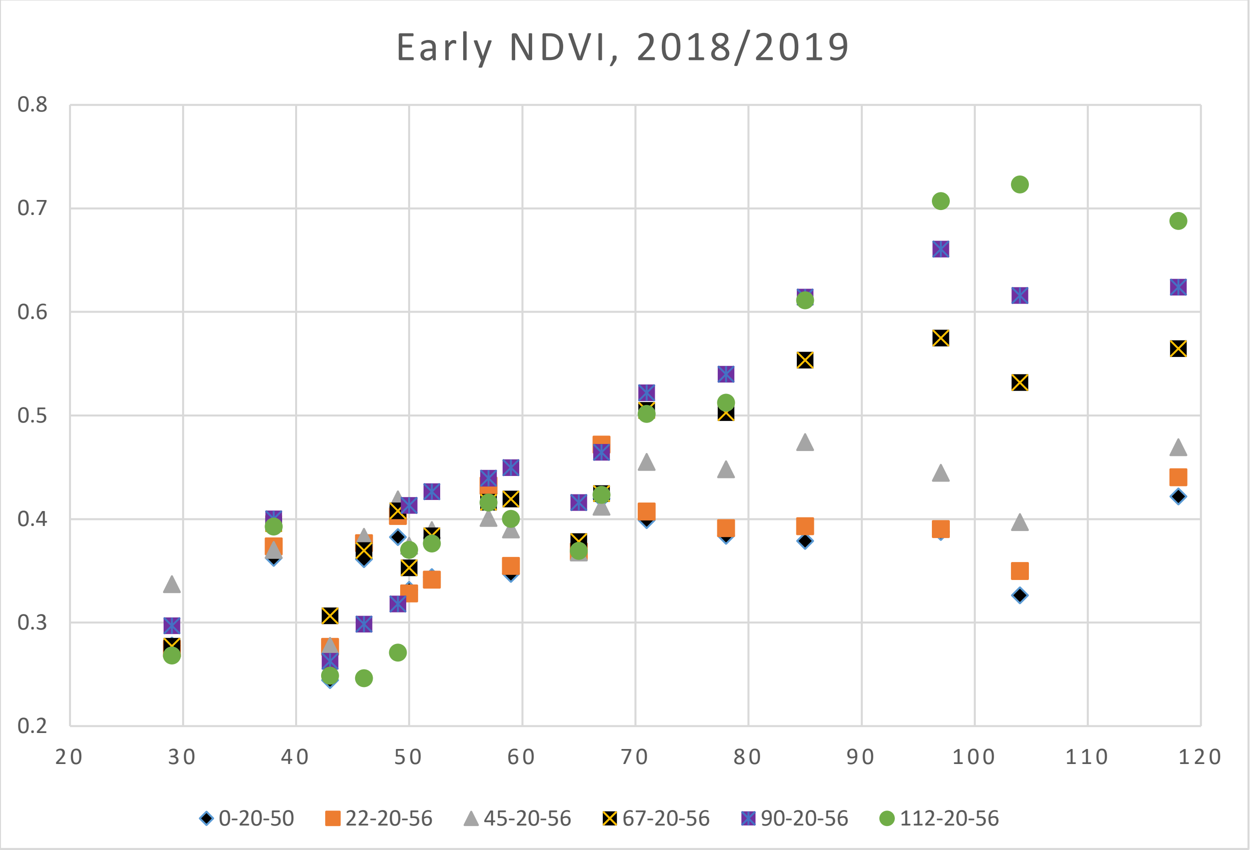

Figure 2.11: Normalized difference vegetative index (NDVI) readings collected from select treatments with in the E502 long term fertility trial in Lahoma, OK over the 2018-2019 growing season (Oct – June). The NDVI values are plotted by GDD > 0, which is a measure the counts any day with an average daily temperature of 4.4C .Treatments utilized for this study were 2 to 7, (0-20-56, 22-20-56, 45-20-56, 67-20-56, 90-20-56, 112-20-56).

Table 2.20: Mean normalized difference vegetative index (NDVI) and coefficient of variation (CV) at different GDD >0

	Average NDVI and CV% for the 4 treatments							
	1		2		3		4	
GDD	NDVI	CV%	NDVI	CV%	NDVI	CV%	NDVI	CV%
16	0.15	1.88	0.15	1.45	0.15	1.52	0.15	3.16
27	0.20	5.11	0.20	3.00	0.20	6.37	0.20	5.08
30	0.19	4.54	0.19	2.08	0.19	2.89	0.19	3.87
36	0.20	10.28	0.19	5.69	0.19	6.90	0.20	8.93
44	0.19	6.62	0.20	9.87	0.20	10.74	0.20	7.99
46	0.20	9.08	0.21	9.37	0.20	20.06	0.21	6.86
48	0.33	14.18	0.33	12.38	0.33	6.22	0.32	8.23
49	0.35	5.03	0.31	7.76	0.29	4.82	0.30	9.84

50	0.51	25.07	0.49	24.06	0.45	20.15	0.48	26.91
52	0.39	13.02	0.40	11.85	0.41	14.44	0.39	16.77
57	0.39	9.93	0.44	17.55	0.41	14.65	0.38	13.84
59	0.39	9.93	0.44	17.55	0.41	14.65	0.38	13.84
65	0.36	2.07	0.36	5.17	0.35	5.13	0.38	6.93
66	0.39	13.29	0.38	12.86	0.38	10.27	0.43	16.61
79	0.45	21.85	0.46	11.52	0.45	15.06	0.43	13.42
99	0.47	25.55	0.50	19.18	0.47	23.05	0.46	19.88

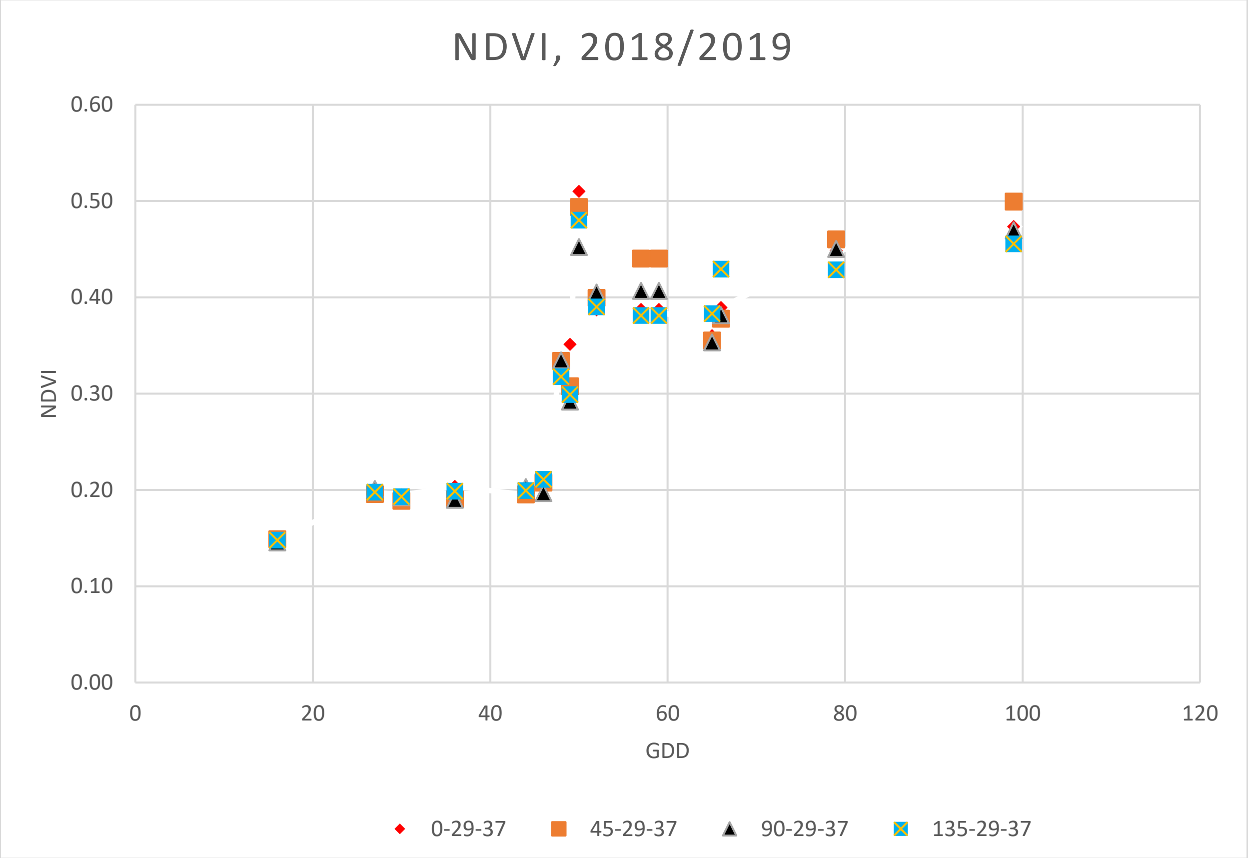

Figure 2.12: Normalized difference vegetative index (NDVI) readings collected from select treatments with in the E222 long term fertility trial in Stillwater, OK over the 2018-2019 growing season (Oct – June). The NDVI values are plotted by GDD > 0, which is a measure the counts any day with an average daily temperature of 4.4C .Treatments utilized for this study were 1 to 4, (0-29-37, 45-29-37, 90-29-37, 135-29-37).

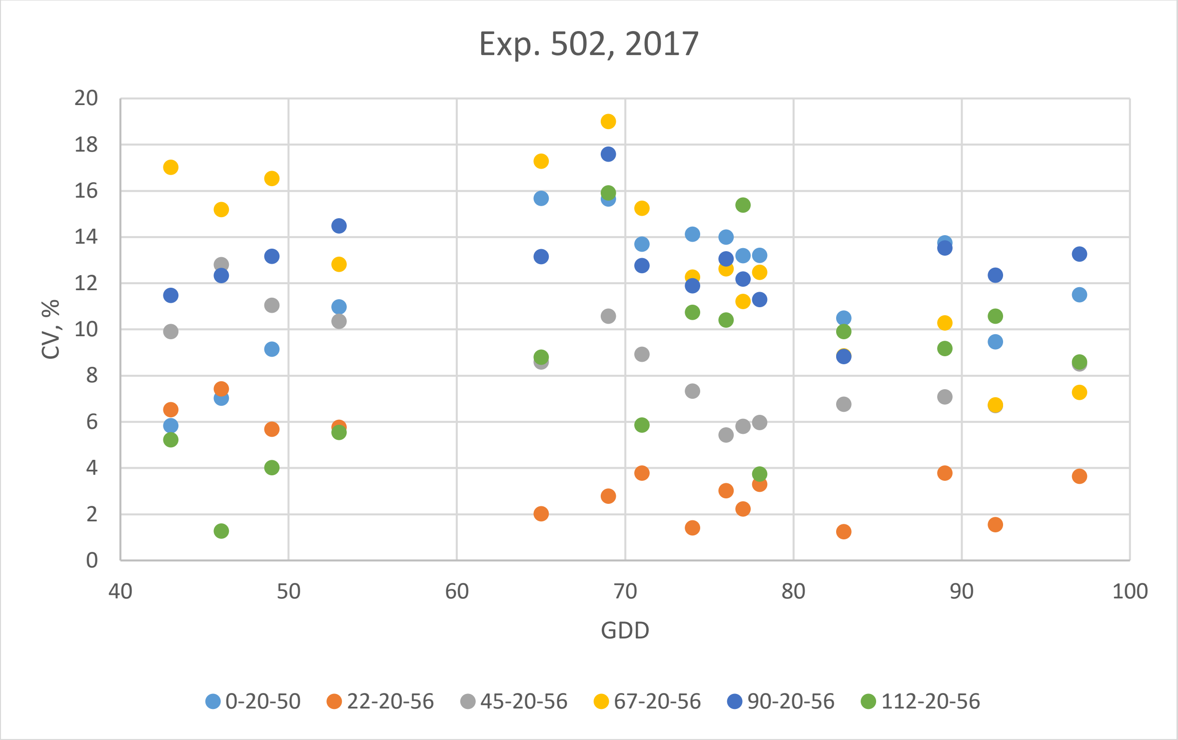

Figure 2.13: Coefficient of variation (CV) calculated from normalized difference vegetation index (NDVI) from select treatments with in the E502 long term fertility trial in Lahoma, OK over the 2017-2018 growing season (Oct – June). The CV values are plotted by GDD > 0, which is a measure the counts any day with an average daily temperature of 4.4C .Treatments utilized for this study were 2 to 7, (0-20-56, 22-20-56, 45-20-56, 67-20-56, 90-20-56, 112-20-56).

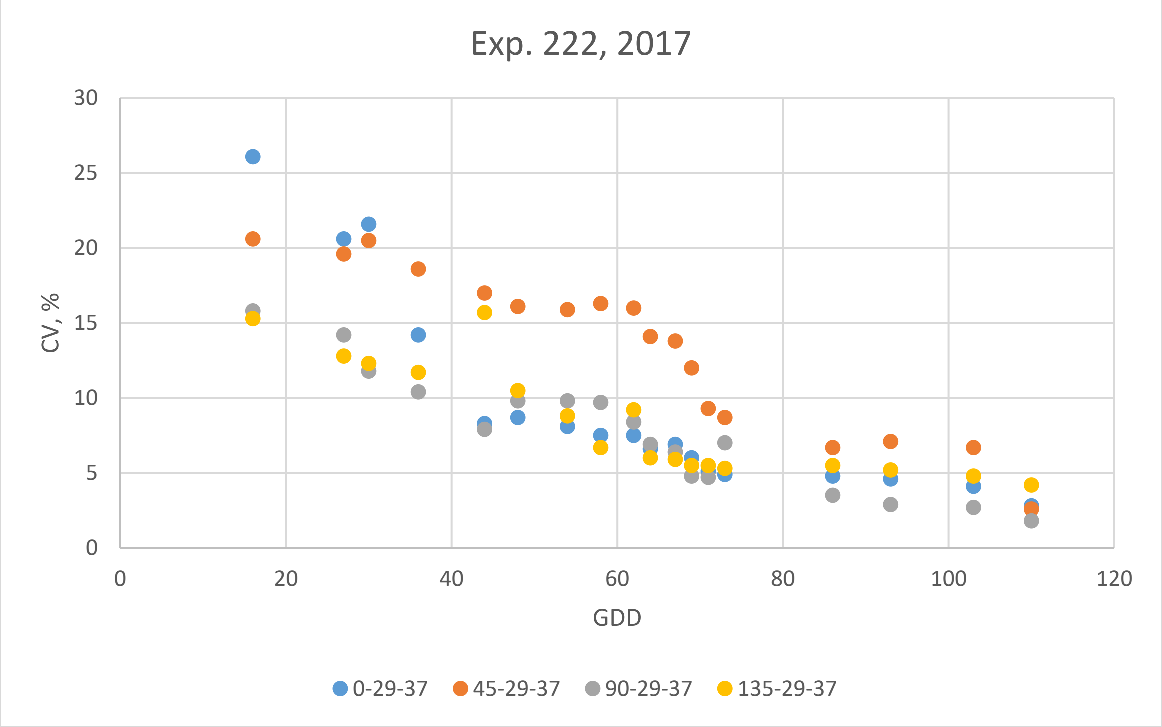

Figure 2.14: Coefficient of variation (CV) calculated from normalized difference vegetation index (NDVI) from select treatments with in the E222 long term fertility trial in Stillwater, OK over the 2017-2018 growing season (Oct – June). The CV values are plotted by GDD > 0, which is a measure the counts any day with an average daily temperature of 4.4C .Treatments utilized for this study were 2 to 7, (0-29-37, 45-29-37, 90-29-37, 135-29-37).

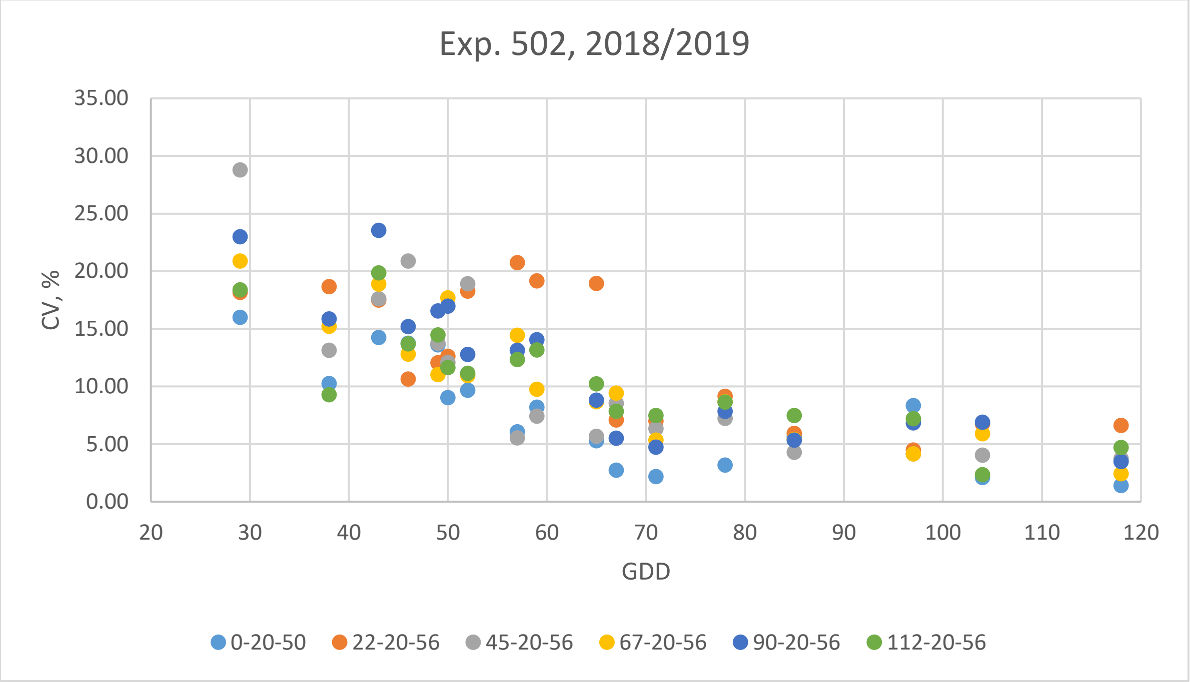

Figure 2.15: Coefficient of variation (CV) calculated from normalized difference vegetation index (NDVI) from select treatments with in the E222 long term fertility trial in Lahoma, OK over the 2018-2019 growing season (Oct – June). The CV values are plotted by GDD > 0, which is a measure the counts any day with an average daily temperature of 4.4C .Treatments utilized for this study were 2 to 7, (0-20-50, 22-20-56, 45-20-56, 67-20-56, 90-20-56, 112-20-56).

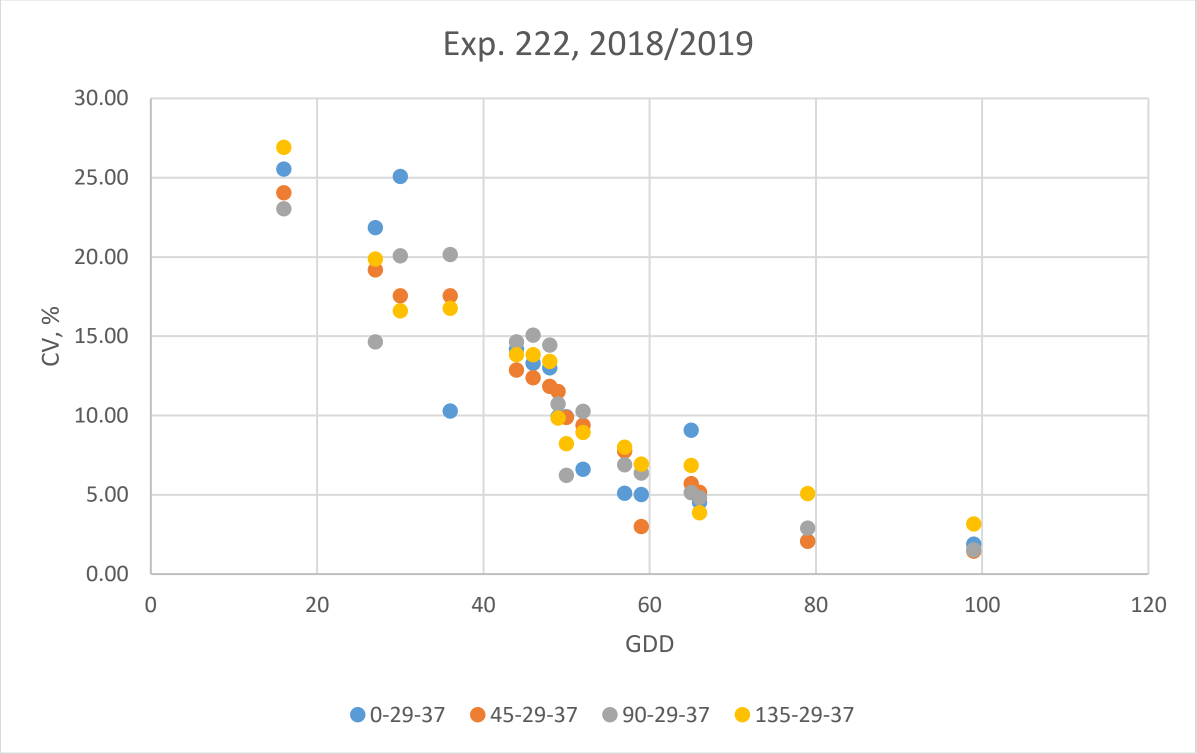

Figure 2.16: Coefficient of variation (CV) calculated from normalized difference vegetation index (NDVI) from select treatments with in the E222 long term fertility trial in Stillwater, OK over the 2018-2019 growing season (Oct – June). The CV values are plotted by GDD > 0, which is a measure the counts any day with an average daily temperature of 4.4C .Treatments utilized for this study were 1 to 4, (0-29-37, 45-29-37, 90-29-37, 135-29-37).

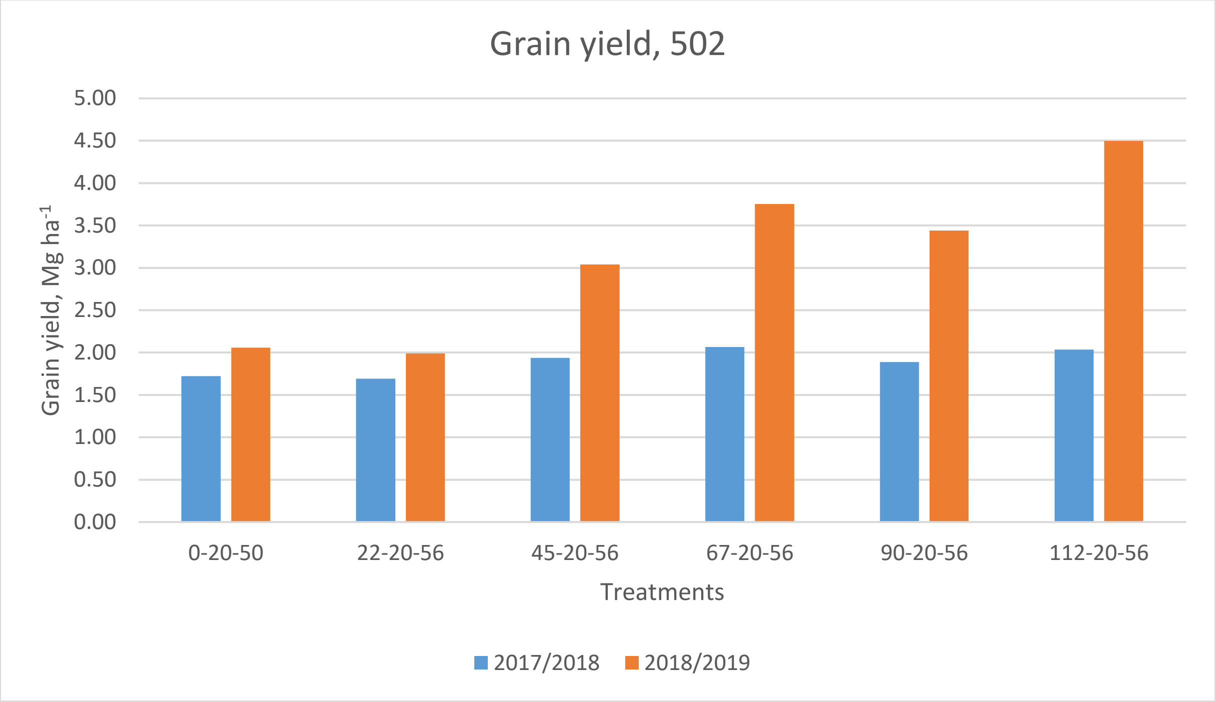

Figure 2.17: Grain yield for Exp.502

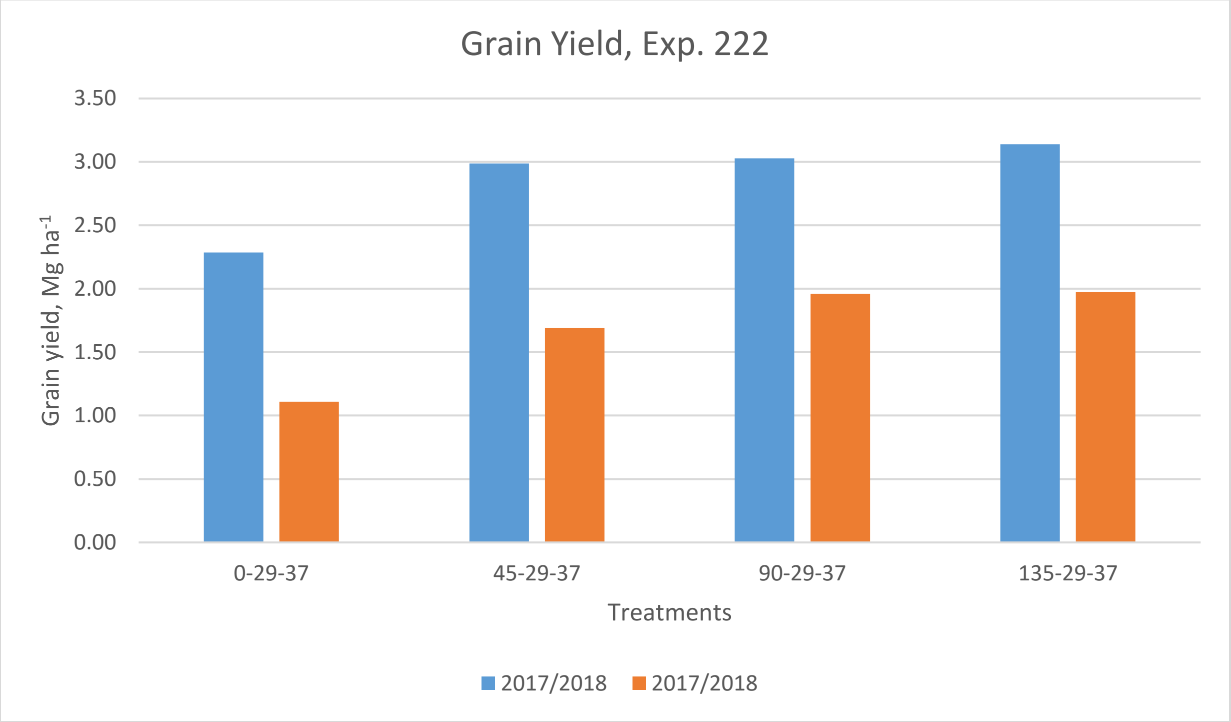

Figure 2.18: Grain yield for Exp.222

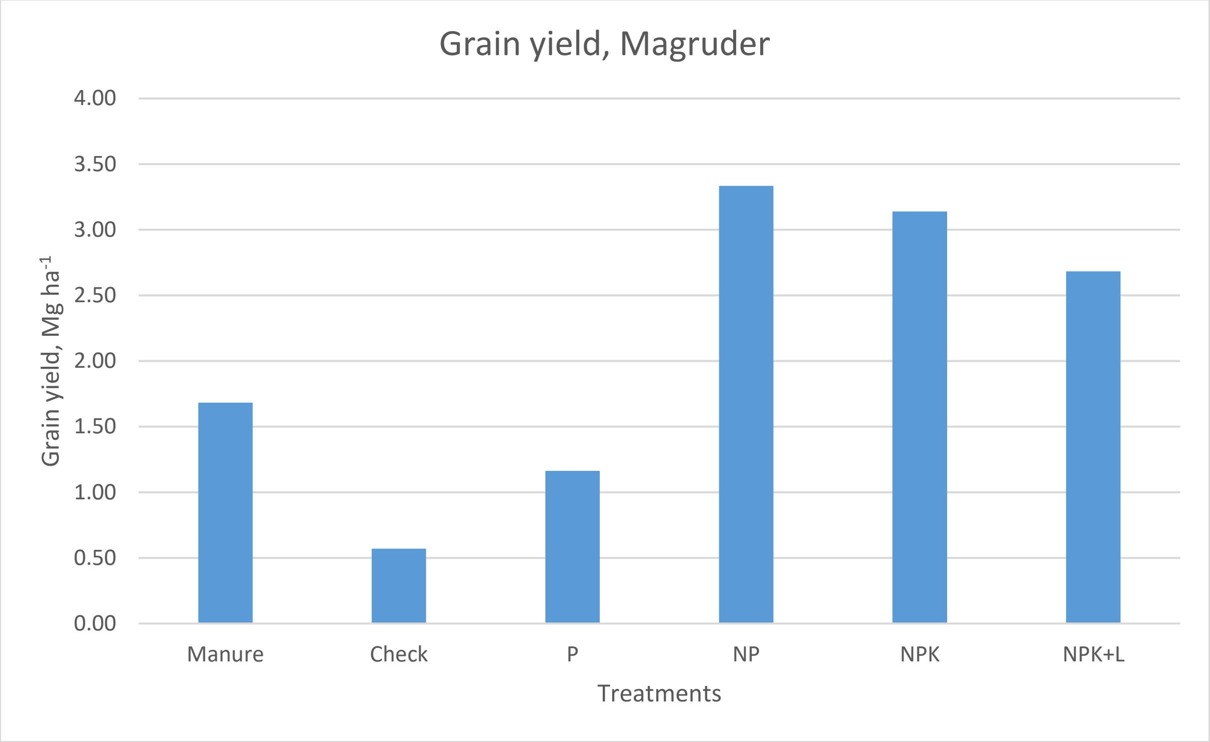

Figure 2.19: Grain yield for Magruder Plots in 2017-2018

Table 2.21: Mean grain yield for Exp. 502, 222 and Magruder Plots

	Exp. 502			Exp.222	
Trt	2017/2018	2018/2019	Trt	2017/2018	2018/2019
0-20-50	1.72	2.06	0-29-37	2.28	1.11
22-20-56	1.69	1.99	45-29-37	2.99	1.70
45-20-56	1.94	3.04	90-29-37	3.03	1.96
67-20-56	2.07	3.76	135-29-37	3.14	1.97
90-20-56	1.89	3.44			
112-20-56	2.03	4.50			
	Magruder				
Manure	1.68				
Check	0.57				
P	1.16				
NP	3.33				
NPK	3.14				
NPK+L	2.68				

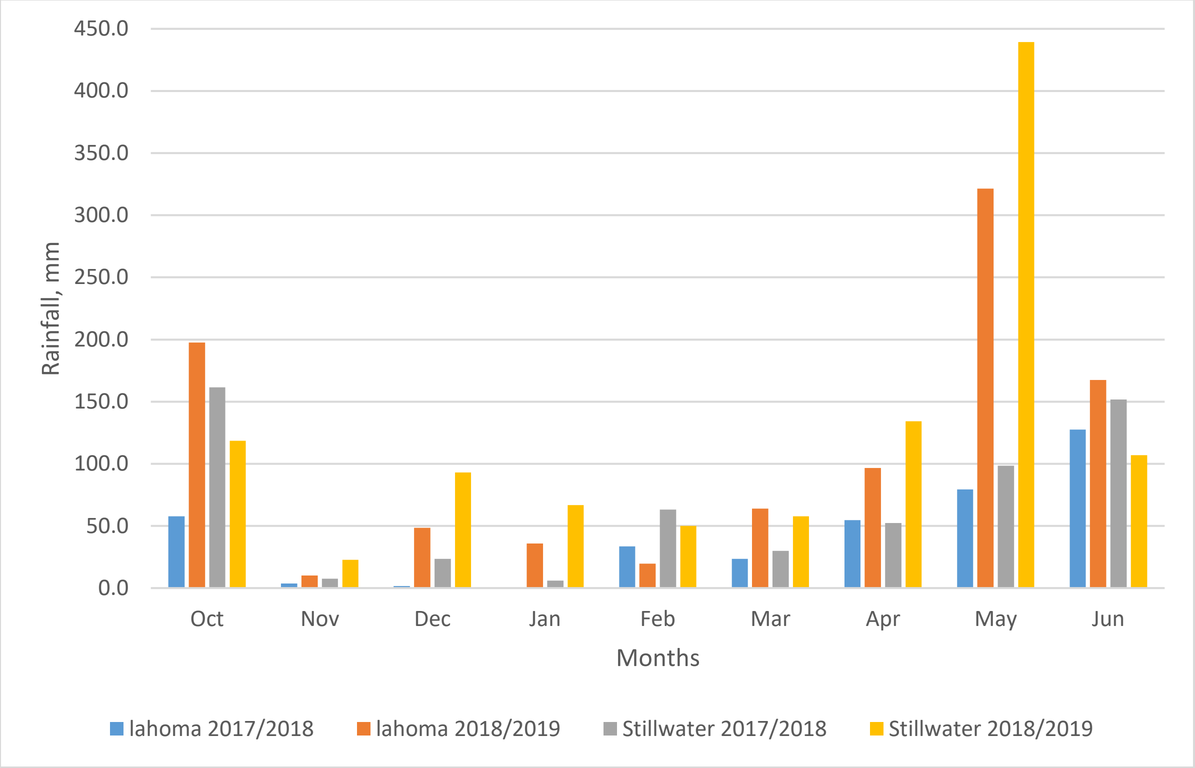

Figure 2.20: Average rainfall for Lahoma and Stillwater locations

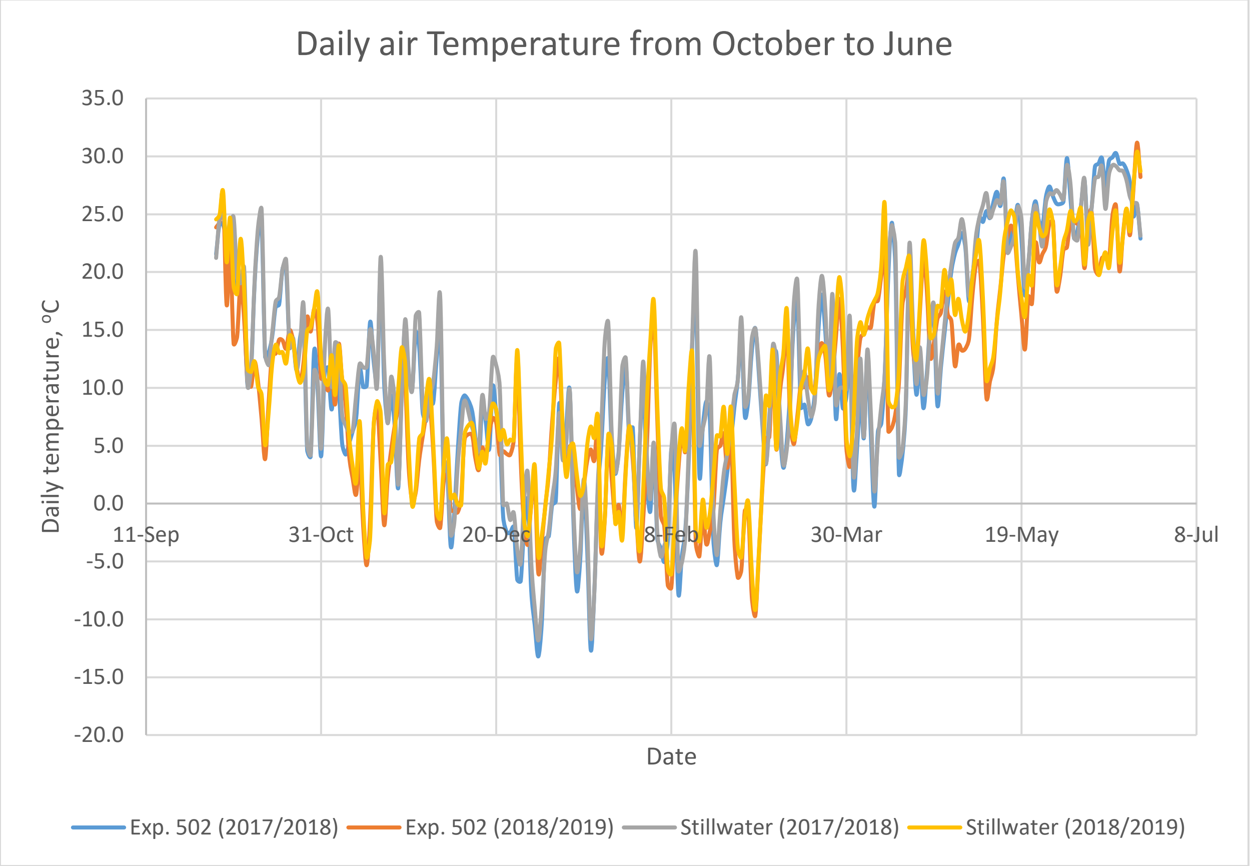

Figure 2.21: Daily air temperature for Lahoma and Stillwater locations from October to June.

VITA

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Doctor of Philosophy

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