OPTIMUM NITROGEN RATE AND PLACEMENT IN HARD RED WINTER WHEAT (Triticum aestivum L)

By

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Abstract: Nitrogen use efficiency (NUE) in cereal crops is at 33% on a global scale. Winter Wheat (*Triticum aestivum*) is one of the major cereal crops being affected by low NUE. Winter wheat is grown across the United States and the world alike and nitrogen is one of the most applied plant nutrients to winter wheat. With great abundance and low world efficiency rates, the need for increasing NUE is paramount. This study looked at varying nitrogen rates, their placement mid-season, and their effects on grain yield. Actual application took place between Growing Degree Days (GDD) greater than zero (GDD > 0) of 90 and 110 to supply the plant with the precise amount of nitrogen needed before its largest vegetative growth stage. The study was conducted in 2020 at four locations across Oklahoma: Lahoma, Hennessey, Perkins, and Stillwater. All studies employed a randomized complete block design with Urea Ammonium Nitrate (UAN) (28-0-0) as the only nitrogen source used. Placement of the UAN was varied between surface applied and sub-surface applied, nitrogen rates varied between 0 kg/ha to 168 kg/ha. Results of this study were mainly inconclusive to the hypothesis that mid-season subsurface applied UAN would yield higher than surface applied UAN at similar N-rates. The supporting optical sensor reading data was also inconclusive. The most significant differences were higher yields when UAN was surface applied. High yields when UAN was surface applied was attributed to the high amount of precipitation that occurred shortly after the midseason application.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Nitrogen (N) is the most needed macronutrient for cereal crop production. It significantly affects leaf area, dry weight biomass, and photosynthetic efficiency. Due to its critical role in plant growth; it is also the most abundantly applied nutrient (Plaza-Bonilla et al., 2017). In 2017, approximately 11 million metric tons of N were applied in the United States alone (FAOSTAT, 2017). Nitrogen is essential in numerous cellular processes in any living plant and is a fundamental component of amino acids, proteins, and DNA synthesis. A plant's photosynthetic capabilities are also directly correlated with N uptake. Since N is applied in such vast quantities it is crucial that the N applied is taken up by the plant and not inadvertently polluting the environment. Lack in efficiency not only pollutes the environment, but simultaneously causes financial loss for the producers themselves. Creating techniques to maximize N uptake is known as nitrogen use efficiency (NUE).

Nitrogen use efficiency is defined as the production of grain per unit of available N in the soil (Moll et al., 1982). Only 33% of N applied to cereal crops are taken up, resulting in the other 67% supplied worldwide to be wasted. Work by Raun and Johnson(1999) showed that N loss can occur through multiple avenues: denitrification (Burford and Brenner, 1975; Olsen et al., 1979, Burkart and James, 1999) ammonia volatilization, runoff (Gascho et al., 1998; Burkart and James, 1999) and leaching (Goss and Goorahoo, 1995; Paramasivam and Alva, 1997). Nitrogen loss due to environmental loss pathways can be widely reduced by implementing different management techniques at the field level. Large N losses often occur due to inefficient N application methods across the globe. One common inefficient practice consists of one high rate of N being applied pre-plant in the form of anhydrous ammonia. Furthermore, most growers also over apply N in fear of under fertilizing their wheat crop, avoiding over application of N is one of the simplest ways to improve NUE (Wuest and Cassman 1992).

Wheat is not only needed to feed the world population but its production also is used to produce economic support of the livelihoods of American farmers. In the United States alone, 37,586,408 acres of wheat were planted and harvested in 2017 (FAOSTAT, 2017). When producers follow NUE practices it does not only protect the environment, but it also gives optimal economic return as they spend less money on fertilizer.

Objective:

To optimize NUE and maximum yield potential in winter wheat with split application of N between pre-plant and midseason applications at different rates, and to exploit the relationship with sub-surface injection versus surface applied UAN (28-0-0).

CHAPTER II

REVIEW OF LITERATURE

Importance of Nitrogen placement

When applying N there are multiple logistical options that can be used to accomplish equally successful fertility goals. Producers use either: granular based urea that is applied to the surface of the soil, gaseous based anhydrous ammonia that is knifed into the soil, or liquid urea ammonium nitrate (UAN) that can either be surface applied in bands, or sub surface applied with a disc. Bryant-Schlobohm (2020) conducted study to evaluate the effects of UAN injected at different depths of the soil profile to evaluate the effects of grain N uptake and what effects N application has on grain yield (Bryant-Schlobohm, 2020). In Bryant-Schlobohm's study they found that placement at depth has the highest impact on grain yield at low N rates, and that subsurface application of N was most beneficial in low N treatments in no-till soils. Surface treatments, however, produced higher yields in low N treatments in conventional tilled soils. Three of the four locations experienced higher rates of N uptake from subsurface applications when compared with surface treatments, and subsurface N applications were beneficial in reducing rates of ammonia volatilization from urea-based fertilizers.

When either granular urea or liquid UAN is applied to the surface there are chances that the N is lost via volatilization (Zhao-Hui Wang et al., 2004). Ammonia volatilization is exacerbated when dry conditions follow the N application. As a whole N response is variable due to environment (Nagelkirk, 2016). With large environmental variability comes the negative effects of lower crop fertility and wasted economic value. Environmental effects can be minimized when liquid UAN is applied subsurface with use of a coulter applicator. When applying UAN in the soil profile, liquid UAN is released multiple centimeters below the soil surface near the root zone of the crop and away from the atmosphere, lowering the amount of UAN lost to volatilization. However, it is also possible to observe little to no differences in application technique like observed in Afshar's study (R. K. Afshar et al., 2021). A multitude of differences arise from external factors, including as previously stated, environmental conditions. Yearly environmental variation being larger than geographic location (Nagelkirk, 2016). Nitrogen rate itself has a varying effect due to year, treatment, location, and wheat variety. Omara's 19 site year study in Oklahoma illustrates this as there is high 29.3% variance form year to year. This high variation stems from the mobile nature of N in the soil profile.

Oklahoma participates in both no till and conventional tillage with this, where the effectiveness of N placement does vary from one cultural method to another. With tillage practices, liquid UAN and granular urea can be surface applied then incorporated into the soil profile with much lower rates of volatilization. No-till operations suffer the most, as it is difficult to incorporate the N fertilizer into the soil, protecting it from the atmosphere. Rochette conducted a study looking at Urea volatilization in conventional till contrasted with volatilization in no-till in 2009. Rochette found hydrolysis of urea occurred very rapidly in no-till soils as indicated by enhanced NH_3 emissions 4 hours after application of urea. The presence of crop residues at the surface of no-till soils also decreased contact of the urea granules with the soil, possibly reducing adsorption of NH_4^+ on soil particles. Lower volatilization on the Conventional till soils may also have partly resulted from a fraction of urea granules falling into shallow cracks. No-till operations thus benefit the most from subsurface application of liquid UAN (Rochette et al., 2009).

Importance of Nitrogen timing

N timing is crucial to maximize both yield and NUE. When N fertilizer is applied in large amounts at the beginning of the growing season as pre-plant fertilizer it has time to denitrify (Burford and Brenner, 1975; Olsen et al., 1979, Burkart and James, 1999) volatilize, runoff (Gascho et al., 1998; Burkart and James, 1999) and leach (Goss and Goorahoo, 1995; Paramasivam and Alva, 1997), because the majority of the N fertilizer will not be needed until the plant goes through large vegetative growth. The way to overcome nitrogen-timing complications is to apply N mid-season, specifically at Feekes stage 5, which generally occurs 97 to 112 Growing Degree Days (GDD). Growing Degree Days are mathematically defined as (Tmin +Tmax)/2 – 4.4°C. Dhillon in 2019 conducted a study in Oklahoma to determine the ideal point in the growing season when NDVI sensor readings were highly correlated with grain yield, Dhillon found after averaging over 3 years (2016–2018), the optimum GDD > 0 needed to predict grain yield using NDVI in both long-term trials was between 97 and 112. Furthermore GDDs ranging from 97 to 112 is optimal for N fertilizer application as this is the time directly before stem elongation. Feekes stage 5 is where the crop puts on the majority of the biomass, thus requiring ample amounts of N fertilizer to be present in the soil (Dhillon et al., 2019).

Importance of optical sensor readings

The application of sensor technology to agricultural systems grows each passing year as its application can be used to make in-season N application recommendations for a wide variety of cereal and vegetative crops. Sensor based technologies allow yield to be predicted based off vegetative biomass, specifically off of the Normalized Difference Vegetative Index (NDVI). NDVI is calculated as NDVI=[(NIR-Red)/(NIR+Red)]. Wavelengths for NIR and Red are (780 nm) and (671nm) respectively (Mullen et al., 2003). Raun et al., 2001 noted that NDVI readings can serve as an in-season yield predictor for wheat. NDVI values ultimately allow yield to be accurately predicted in the middle of the growing season. Top-dress applications of N can then be applied to meet crop yield demands and thus potentially achieve higher NUE. Macnack (2014) conducted a 3 year study to evaluate, grain yield, NUE, and grain protein as a function of rate and timing of N fertilizer application. Linear models were used to evaluate the effect of pre-plant N, NDVI, cumulative rainfall and average air temperature from planting to sensing date. GreenSeeker readings were collected at Feekes 3, 4, 5, and 7 growth stages. Combined with rainfall and/or average temperature, NDVI alone was not correlated with NUE. However, NDVI and rainfall explained 45% (r2 = 0.45) of the variability in GP at F7 growth stage (Macnack, 2014)

CHAPTER III

MATERIALS AND METHODS

Four winter wheat experiments were carried out to determine the appropriate rate/method of N management in winter wheat so as to optimize NUE, and grain yields. Field experiments were carried out at four locations in Oklahoma: Perkins, Efaw, Hennessey, and Lahoma. All locations are representative of the dryland wheat conditions across the United States. Soil classification at the Efaw research station is Ashport silty clay loam; fine-silty, mixed, superactive, thermic Fluventic Haplustolls, Lahoma research station is located on a Grant silt loam; fine-silty, mixed, superactive, thermic Udic Argiustolls, Hennessey soils are a Bethany silt loam; fine, mixed, superactive, thermic Paleustoll, and lastly Perkins is located on a Teller; fine-loamy, mixed, active, thermic Udic Agriustoll (Soil Survey, 2021). All experiments took place across the 2019-2020 growing season. Previous cropping history of each site location was continuous winter wheat. Trials were planted mid-October and harvested the following June (Table 7).

Treatment structure of this experiment included an unfertilized control and an N-rich strip applied with 168 kg ha^{-1} along with two methods of application (surface and subsurface) and six rates of top-dressed N application. All treatments, except the unfertilized check and the N-rich strip were applied 28 kg ha^{-1} pre-plant. Treatment plots were 3 meters wide and 6.1 meters long with 3 meter alleyways between reps. Treatments were arranged in a randomized complete block experimental design with three replications per site. Liquid Urea Ammonium Nitrate (UAN) was applied either pre-plant or mid-season/surface applied, and was either applied to the surface or was applied to the surface of the soil via spray nozzles. Subsurface N application utilized a disc cultivator applicator in which UAN was dripped beneath the surface approximately 2.54 cm next to the seed furrow. Liquid UAN was applied with varying pressures and speeds on equipment to reach the rate desired for each treatment. Mid-season application of UAN both surface and subsurface was preformed between 97 to 112 GDD > 0, occurring around Feekes stage 5.

Prior to planting, composite soil samples were taken by replication to a depth of 0-15 cm. Fifteen cores per replication were taken at each location. Soil samples were collected to get an accurate baseline record of the soil nutrient concentrations before the experimental factors were introduced, (Table 2).

Over all four locations commercial pesticides such as Glyphosate, Zidua, Weedmaster, Paraquat, and 2,4-D LV6 were used throughout the year to reduce the potential damage of weeds and insects. A Great Plains and a John Deere no-till drill were used for wheat planting. Conventional till sites were chisel plowed before planting for preparation of the seedbed. NDVI readings were taken approximately every two weeks, near Feekes stages 3, 4, 5, and 7. NDVI readings were taken with a hand held active sensor, Trimble GreenSeeker. All plots were harvested with a Kincaid 8-XP small plot combine, equipped with a harvest master yield monitor for measuring yield. Rainfall and temperature data was extracted from the Oklahoma Mesonet weather stations throughout Oklahoma.

Statistical software, SAS 9.3 was used for analysis. A generalized linear model was used to generate treatment means and analyze treatment effects. The linear model included application method, pre-plant N rate, and top-dress N rate as fixed effects and replication as a random effect.

The standard error of the difference (SED) was then calculated using the formula $SED= \sqrt{((2*MSE)/Rep)}$ and reported. Single-degree-of-freedom contrast comparisons were used to determine significant treatment differences at an alpha level of 0.05.

CHAPTER IV

RESULTS AND DISCUSSION

Perkins 2020

Sensor based NDVI readings were taken three separate times throughout the growing season, 77, 81, 93 GDDs > 0, respectively (Table 3). In season data was insignificant across all treatment contrasts and across all four readings. Coefficient of determination (R^2) values for each reading follow: (77 GDD > 0, $R^2 = 0.1247$), (81 GDD > 0, $R^2 = 0.0714$), and (93 GDD > 0, $R^2 = 0.1067$), (Figure 1). No significant differences in grain yield were observed across treatments. The lowest yielding treatment was the Check at 3.90 Mg ha^{-1} and the highest being treatment 7, having 112 kg N ha^{-1} surface applied, topping out at 5.61 Mg ha^{-1} (Table 3). One plausible reason into why the subsurface injection faired equal to the surface applied UAN could be the substantial amount of rainfall that was received shortly after the mid-season application of UAN. March rainfall peaked over 140mm causing a natural incorporation of the surface applied UAN and limiting the amount of volatilization to occur while simultaneously causing the subsurface applied UAN to leach from the rhizosphere (Figure 5). The insignificance of the NDVI correlation to yield is unknown.

Lahoma 2020

Significant treatment differences for yield were observed (Table 4). Sensor based NDVI readings were taken four separate times throughout the growing season, 72, 75, 80, and 92 GDDs

> 0 respectively. Sensor readings were not correlated with grain yield over all four readings but tended to be higher with advancing stage of growth. Coefficient of determination values for NDVI versus yield were below 0.1, (77 GDD > 0, $R^2 = 0.0316$), (75 GDD > 0, $R^2 = 0.0096$), (80 GDD > 0, $R^2 = 0.0174$), and (92 GDD > 0, $R^2 = 0.0855$) (Figure 2). Treatment differences in grain yield were different for various contrast comparisons. Grain yields were significantly higher at $\alpha = 0.05$ level of significance in both (5 v 11) and (6 v 12) with grain values of (2.83 Mg ha^{-1} v 2.32 Mg ha^{-1}) and (3.40 Mg ha^{-1} v 2.83 Mg ha^{-1}). Grain yields for (3 v 9) and (Surface v Subsurface Injection) were significantly different at $\alpha = 0.01$ with grain values being (2.16 Mg ha^{-1} v 1.52 Mg ha^{-1}) and (2.893 Mg ha^{-1} average v 2.51 Mg ha^{-1} average) respectively. The remaining contrasts did not show treatment differences in yield. When considering all grain yield contrasts at this location, contrasts for this effect indicated lower grain yields when N was surface applied. One plausible reason for subsurface injection yielding higher than surface applied UAN could be the substantial amount of rainfall that precipitated shortly after the mid-season application of UAN. March rainfall exceeded 75cm, ultimately causing a natural incorporation of the surface applied UAN and limiting the amount of volatilization to occur while simultaneously causing the subsurface applied UAN to leach from the rhizosphere (Figure 6). The insignificance of the NDVI correlation to yield is unknown.

Hennessey 2020

Sensor based NDVI readings were taken four separate times throughout the growing season, 64, 67, 73, and 91 GDDs > 0 respectively (Table 5). In season NDVI data was not significantly correlated with yield excluding NDVI collected at 91 GDDs > 0 with significance at $\alpha = 0.05$, (2 v 14) Average NDVI values were 0.53 and 0.59 for treatments 2 and 14. This was significant whereby subsurface injection had higher NDVI values. Simple linear regression equations were similar across all four readings, (64 GDD > 0, $R^2 = 0.1197$), (67 GDD > 0, $R^2 = 0.1121$), (73 GDD > 0, $R^2 = 0.114$), and (91 GDD > 0, $R^2 = 0.1198$), Figure 3). Grain yield contrasts only yielded one statistical significant difference where 2 and 8 were different ($\alpha = 0.05$). Grain yield values were 4.50 Mg ha^{-1} and 5.84 Mg ha^{-1} respectively. This illustrated the importance of midseason applied N compared to higher amounts of N applied pre-plant. The remaining NDVI grain yield relationships were not statistically significant at $\alpha = 0.05$. The highest amount of precipitation was found in March nearly eclipsing 100cm. This was when mid-season N was applied; possibly causing a natural incorporation of the surface applied UAN and limiting the amount of volatilization to occur while simultaneously causing the subsurface applied UAN to leach from the rhizosphere. This most likely caused insignificant results of grain yield in surface vs subsurface (Figure 7). The insignificance of the NDVI correlation to yield is unknown.

EFAW 2020

Only one statistically significant NDVI value was observed at this location. NDVI data readings were taken three separate times across the growing season: 77, 81, 100 GDD > 0. The only values showing significance at $\alpha = 0.05$ was (4 v 10), NDVI vales being (0.66 v 0.60). For the contrast comparison treatment 4, 28 kg/ha surface applied had a higher NDVI value than the subsurface applied treatment at the same rate. Values for R^2 (NDVI vs. Yield) were all below 0.05, (77 GDD > 0, $R^2 = 0.0049$), (81 GDD > 0, $R^2 = 0.0416$), and (100 GDD > 0, $R^2 = 0.0855$) (Figure 4). Differences in grain yield over all treatments were small. In season precipitation peaked over 120mm in the month of March (Figure 8). Rainfall occurred after mid-season application of N causing a natural incorporation of the surface applied UAN and limiting the amount of volatilization to occur while simultaneously causing the subsurface applied UAN to leach from the rhizosphere. This most likely caused insignificant results of grain yield in surface vs subsurface. The insignificance of the NDVI correlation to yield is unknown.

CHAPTER V

CONCLUSIONS

The purpose of this winter wheat study was to evaluate the effect of N rate and placement when applied mid-season. The hypothesis was that the mid-season, subsurface applied UAN (28-0-0) would yield positive relationships between NDVI and grain yield. The benefit for incorporated N was not observed at any of the four site years. The relationships between NDVI and grain yield that were significant tended to be coming from those treatments where N was surface applied. Higher grain yields when N was applied as UAN to the surface was hypothesized to have taken place following large amounts of rain recorded at all four locations, and shortly after mid-season application of N had been applied. High rainfall accumulation served as a natural physical force that incorporated surface applied N. Most grain yield vs NDVI data showed limited correlation over sites. Experimental error and excess rainfall were likely causes of this observation.

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APPENDICES

Table 1.) Treatment structure, Perkins 2019-2020, Lahoma 2019-20220, Hennessey 2019-2020, EFAW 2019-2020

Treatment	Method	Preplant N, kg/ha	Topdress N, kg/ha
1	Check	0	0
2	N-Rich	168	0
3	Surface	28	0
4	Surface	28	28
5	Surface	28	56
6	Surface	28	84
7	Surface	28	112
8	Surface	28	140
9	Sub-Surface	28	0
10	Sub-Surface	28	28
11	Sub-Surface	28	56
12	Sub-Surface	28	84
13	Sub-Surface	28	112
14	Sub-Surface	28	140

Table 2.) Preplant Soil Test data: Soil pH, Nitrate-N, ammonium-N, potassium, and phosphorus

Year	Location	rep.	pH	K mg/kg	ICAP P mg/kg	NO3-N mg/kg	NH4-N mg/kg
2019-20	Lahoma	1	5.84	395	84	6	14
2019-20	Lahoma	2	5.73	379	82	4.5	13
2019-20	Lahoma	3	5.63	378	81	6	14
2019-20	Hennessey	1	5.07	111	22	16	19.5
2019-20	Hennessey	2	5.07	110	22	15.5	16
2019-20	Hennessey	3	5.08	108	21	12	20
2019-20	Perkins	1	5.72	137	36	7	19.5
2019-20	Perkins	2	5.72	122	31	6.5	24
2019-20	Perkins	3	6.18	102	26	10	24
2019-20	EFAW	1	7.04	238	8	13.5	17
2019-20	EFAW	2	6.39	226	8	13.5	25.5
2019-20	EFAW	3	5.34	217	10	16.5	20.5

Table 3.) Treatment structure and associated means for yield and NDVI at three different stages, and significance of single-degree-of-freedom contrasts, Perkins, OK, 2019-2020.

Treatment	Preplant N Rate (kg N ha-^{1})	Mid-season Rate (kg N ha-^{1})	NDVI, GDDs >0			Grain Yield (Mg ha-^{1})
			77	81	93	
1	0	0	0.40	0.33	0.42	3.90
2	168	0	0.41	0.35	0.44	5.08
3	28	0	0.41	0.35	0.47	4.28
4	28	28	0.39	0.33	0.42	4.43
5	28	56	0.42	0.35	0.44	4.76
6	28	84	0.41	0.36	0.46	5.15
7	28	112	0.40	0.33	0.43	5.61
8	28	140	0.40	0.35	0.47	5.13
9	28	0	0.42	0.37	0.46	4.22
10	28	28	0.41	0.33	0.43	4.87
11	28	56	0.40	0.35	0.45	4.90
12	28	84	0.44	0.38	0.47	5.42
13	28	112	0.41	0.35	0.45	5.17
14	28	140	0.39	0.33	0.42	4.38
SED			0.02	0.22	0.03	0.27
CV%			6.36	7.82	8.39	6.96
Contrasts						
Surface vs Subsurface injection			ns	ns	ns	ns
Trt. 2 vs Trt. 8			ns	ns	ns	ns
Trt. 2 vs Trt. 14			ns	ns	ns	ns
Trt. 3 v Trt. 9			ns	ns	ns	ns
Trt. 4 v Trt. 10			ns	ns	ns	ns
Trt. 5 v Trt. 11			ns	ns	ns	ns
Trt. 6 v Trt. 12			ns	ns	ns	ns
Trt. 7 v Trt. 13			ns	ns	ns	ns

NDVI- normalized difference vegetative index, GDD>0 – growing degree-days > 0. SED – standard error of the difference between two equally replicated means, CV – coefficient of variation, ns - not significant, * - significant at α = 0.05, ** - significant at α = 0.01

Table 4.) Treatment structure and associated means for yield and NDVI at three different stages, and significant of single-degree-of-freedom contrasts, Lahoma, OK, 2019-2020.

	Preplant N Rate (kg N ha-^{1})	Mid-season Rate (kg N ha-^{1})	NDVI, GDDs >0				Grain Yield (Mg ha-^{1})
Treatment			72	75	80	92	
1	0	0	0.28	0.33	0.30	0.53	1.72
2	168	0	0.29	0.34	0.31	0.49	2.82
3	28	0	0.31	0.37	0.34	0.47	2.16
4	28	28	0.31	0.37	0.33	0.47	2.92
5	28	56	0.28	0.34	0.31	0.50	2.83
6	28	84	0.29	0.35	0.31	0.51	3.40
7	28	112	0.29	0.33	0.30	0.51	3.06
8	28	140	0.27	0.32	0.30	0.51	2.99
9	28	0	0.28	0.33	0.30	0.52	1.52
10	28	28	0.31	0.37	0.33	0.47	2.67
11	28	56	0.28	0.31	0.30	0.52	2.32
12	28	84	0.29	0.35	0.32	0.48	2.83
13	28	112	0.29	0.33	0.30	0.49	2.92
14	28	140	0.29	0.32	0.31	0.50	2.80
SED			0.02	0.04	0.28	0.05	0.22
CV%			9.40	13.89	11.08	11.29	10.30
Contrasts							
Surface vs Subsurface injection			ns	ns	ns	ns	**
Trt. 2 vs Trt. 8			ns	ns	ns	ns	ns
Trt. 2 vs Trt. 14			ns	ns	ns	ns	ns
Trt. 3 v Trt. 9			ns	ns	ns	ns	**
Trt. 4 v Trt. 10			ns	ns	ns	ns	ns
Trt. 5 v Trt. 11			ns	ns	ns	ns	*
Trt. 6 v Trt. 12			ns	ns	ns	ns	*
Trt. 7 v Trt. 13			ns	ns	ns	ns	ns

NDVI- normalized difference vegetative index, GDD>0 – growing degree-days > 0. SED – standard error of the difference between two equally replicated means, CV – coefficient of variation) ns - not significant, * - significant at $\alpha = 0.05$, ** - significant at $\alpha = 0.01$

Table 5.) Treatment structure and associated means for yield and NDVI at three different stages, and significant of single-degree-of-freedom contrasts, Hennessey, OK, 2019-2020.

	Preplant N Rate (kg N ha-^{1})	Mid-season Rate (kg N ha-^{1})	NDVI, GDDs > 0				Grain Yield (Mg ha-^{1})
Treatment			64	67	73	91	
1	0	0	0.23	0.25	0.32	0.53	3.58
2	168	0	0.25	0.26	0.33	0.53	4.50
3	28	0	0.24	0.25	0.33	0.52	3.82
4	28	28	0.28	0.30	0.37	0.58	4.72
5	28	56	0.30	0.32	0.36	0.53	5.11
6	28	84	0.27	0.28	0.35	0.53	5.34
7	28	112	0.30	0.31	0.39	0.59	6.33
8	28	140	0.24	0.25	0.33	0.54	5.84
9	28	0	0.29	0.31	0.37	0.56	3.68
10	28	28	0.27	0.28	0.34	0.55	4.92
11	28	56	0.29	0.29	0.35	0.52	5.24
12	28	84	0.29	0.30	0.39	0.57	4.93
13	28	112	0.28	0.30	0.37	0.58	5.86
14	28	140	0.24	0.26	0.33	0.59	5.25
SED			1.73	1.73	0.03	0.03	0.60
CV%			13.17	14.47	11.09	6.57	14.99
Contrasts							
Surface vs Subsurface injection			ns	ns	ns	ns	ns
Trt. 2 vs Trt. 8			ns	ns	ns	ns	*
Trt. 2 vs Trt. 14			ns	ns	ns	*	ns
Trt. 3 v Trt. 9			ns	ns	ns	ns	ns
Trt. 4 v Trt. 10			ns	ns	ns	ns	ns
Trt. 5 v Trt. 11			ns	ns	ns	ns	ns
Trt. 6 v Trt. 12			ns	ns	ns	ns	ns
Trt. 7 v Trt. 13			ns	ns	ns	ns	ns

NDVI- normalized difference vegetative index, GDD>0 – growing degree-days > 0. SED – standard error of the difference between two equally replicated means, CV – coefficient of variation) ns - not significant, * - significant at α = 0.05, ** - significant at α = 0.01

Table 6.) Treatment structure and associated means for yield and NDVI at three different stages, and significant of single-degree-of-freedom contrasts, EFAW, OK, 2019-2020.

	Preplant N Rate (kg N ha-^{1})	Mid-season Rate (kg N ha-^{1})	NDVI, GDDs > 0			Grain Yield (Mg ha-^{1})
Treatment			77	81	100	
1	0	0	0.67	0.61	0.61	2.42
2	168	0	0.69	0.66	0.65	3.43
3	28	0	0.68	0.61	0.62	2.29
4	28	28	0.69	0.66	0.66	4.25
5	28	56	0.67	0.66	0.67	2.99
6	28	84	0.70	0.64	0.63	3.77
7	28	112	0.69	0.60	0.62	2.83
8	28	140	0.69	0.65	0.64	3.91
9	28	0	0.66	0.63	0.62	2.62
10	28	28	0.65	0.59	0.60	4.55
11	28	56	0.68	0.61	0.64	3.37
12	28	84	0.69	0.63	0.63	3.61
13	28	112	0.69	0.64	0.63	2.89
14	28	140	0.68	0.66	0.64	3.73
SED			0.02	0.04	0.03	0.19
CV%			4.44	6.89	5.90	21.53
Contrasts						
Surface vs Subsurface injection			ns	ns	ns	ns
Trt. 2 vs Trt. 8			ns	ns	ns	ns
Trt. 2 vs Trt. 14			ns	ns	ns	ns
Trt. 3 v Trt. 9			ns	ns	ns	ns
Trt. 4 v Trt. 10			ns	ns	*	ns
Trt. 5 v Trt. 11			ns	ns	ns	ns
Trt. 6 v Trt. 12			ns	ns	ns	ns
Trt. 7 v Trt. 13			ns	ns	ns	ns

NDVI- normalized difference vegetative index, GDD>0 – growing degree-days > 0. SED – standard error of the difference between two equally replicated means, CV – coefficient of variation) ns - not significant, * - significant at α = 0.05, ** - significant at α = 0.01

Table 7.) Field activity dates.

	Planting Date	Pre-plant Application Date	Top-dress Application Date	Harvest Date
Perkins	10/12/2019	10/2/2019	2/28/2020	6/8/2020
Lahoma	10/8/2019	9/27/2019	3/6/2021	6/11/2020
Hennessey	10/18/2019	9/27/2019	3/12/2020	6/12/2020
EFAW	10/10/2019	10/2/2019	3/5/2020	6/10/2020

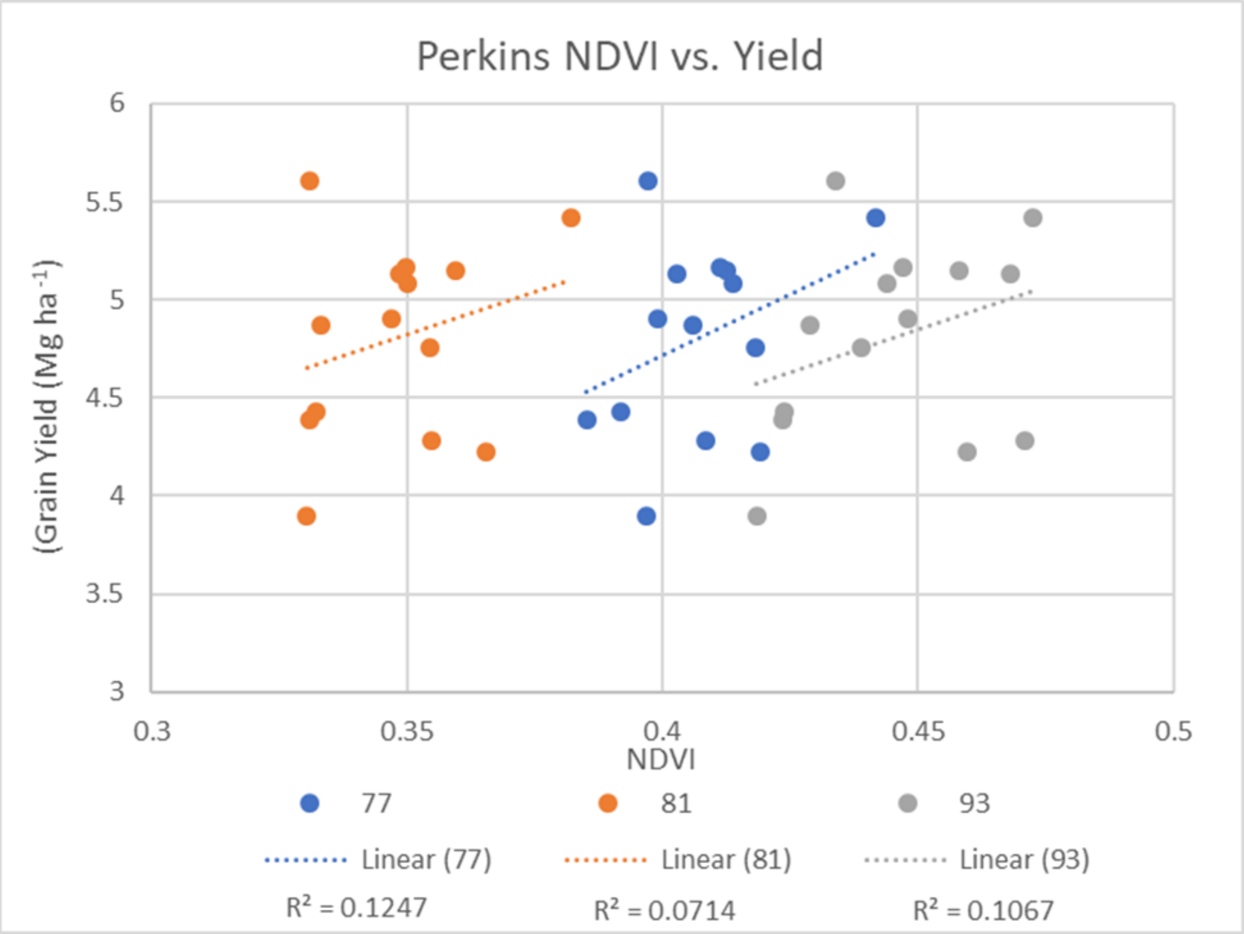

Figure 1.) Correlation between grain yield and NDVI with advancing growth stage or growing degree days (GDD), Perkins, OK 2019-2020.

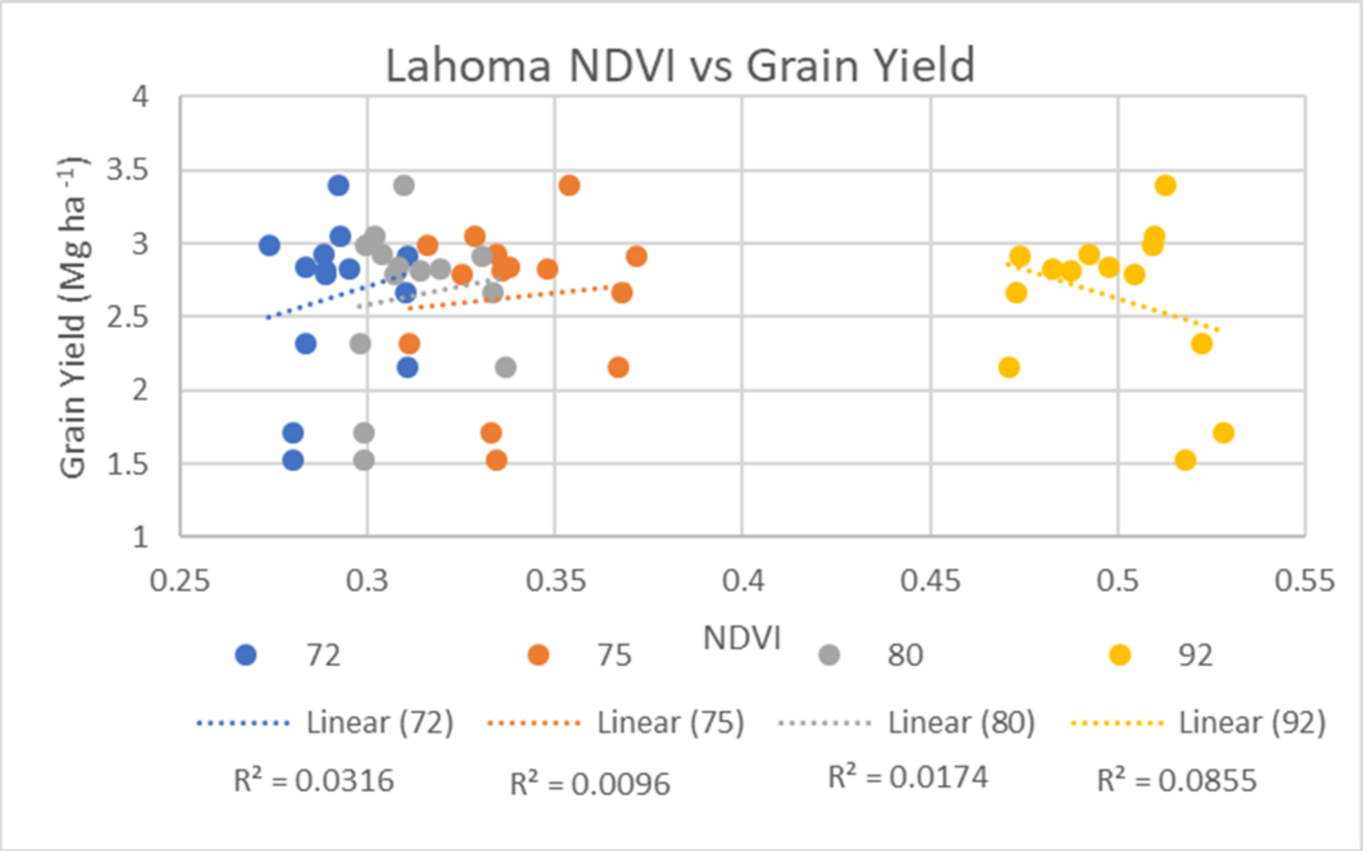

Figure 2.) Correlation between grain yield and NDVI with advancing growth stage or growing degree days (GDD), Lahoma, OK 2019-2020.

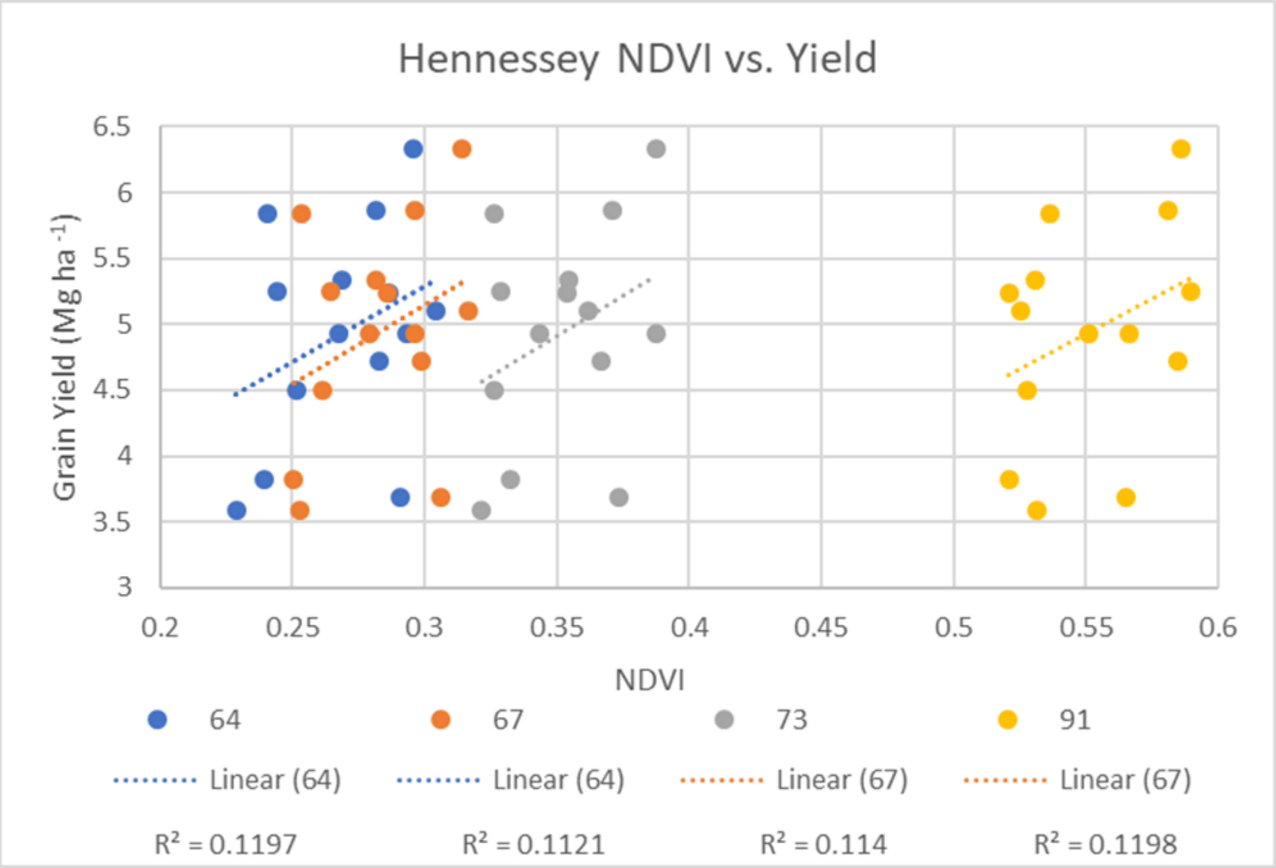

Figure 3.) Correlation between grain yield and NDVI with advancing growth stage or growing degree days (GDD), Hennessey, OK 2019-2020.

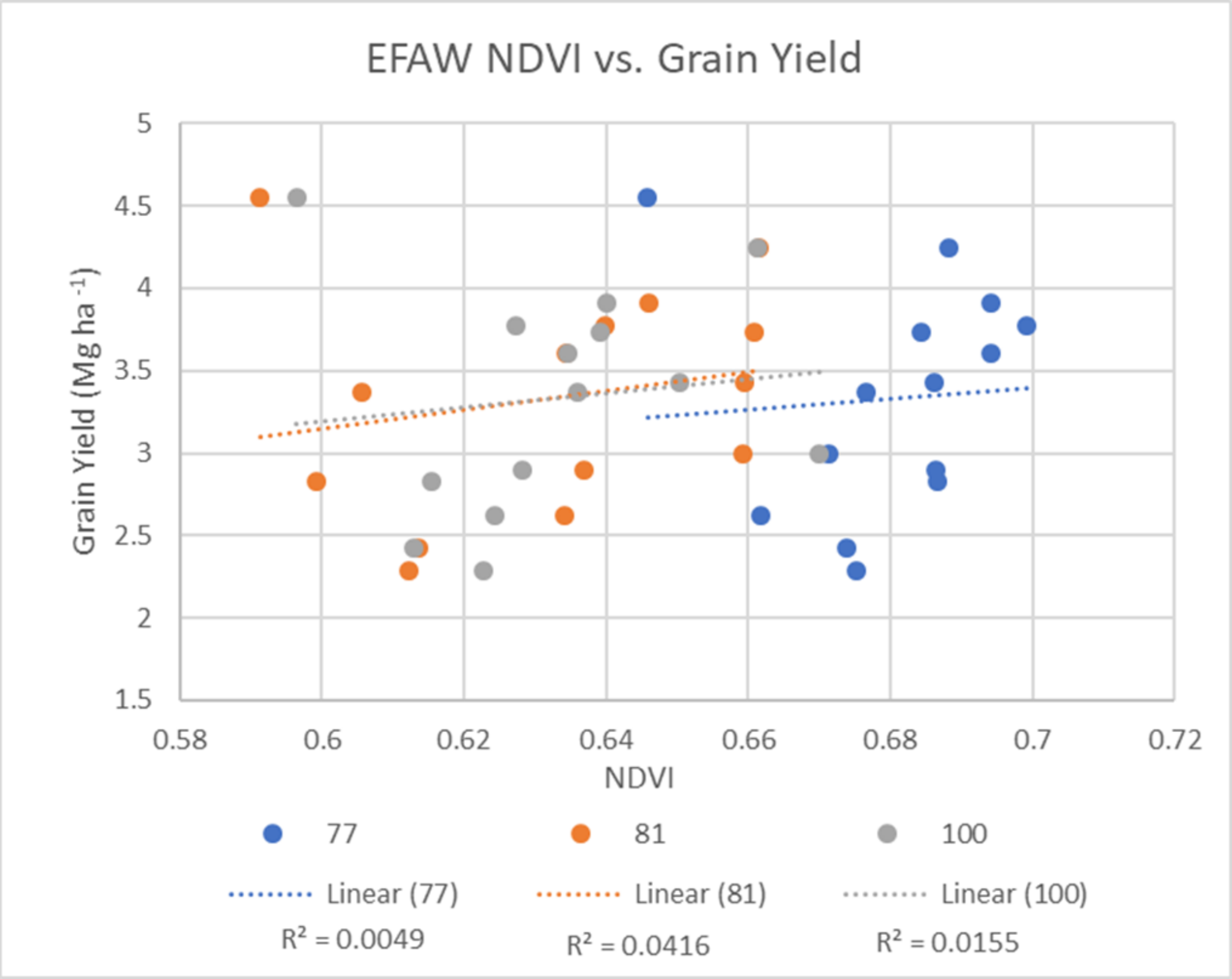

Figure 4.) Correlation between grain yield and NDVI with advancing growth stage or growing degree days (GDD), EFAW, OK 2019-2020.

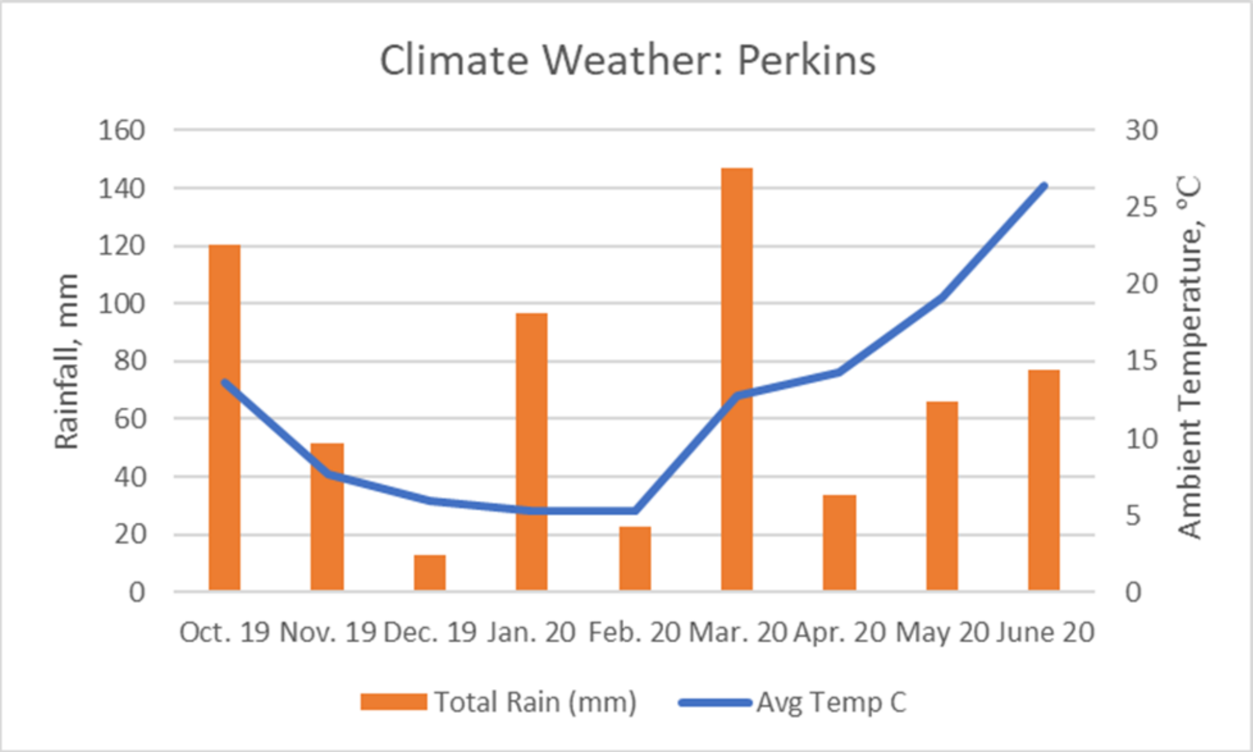

Figure 5.) Average temperature and rainfall by month across the growing season in Perkins, Oklahoma 2019-2020.

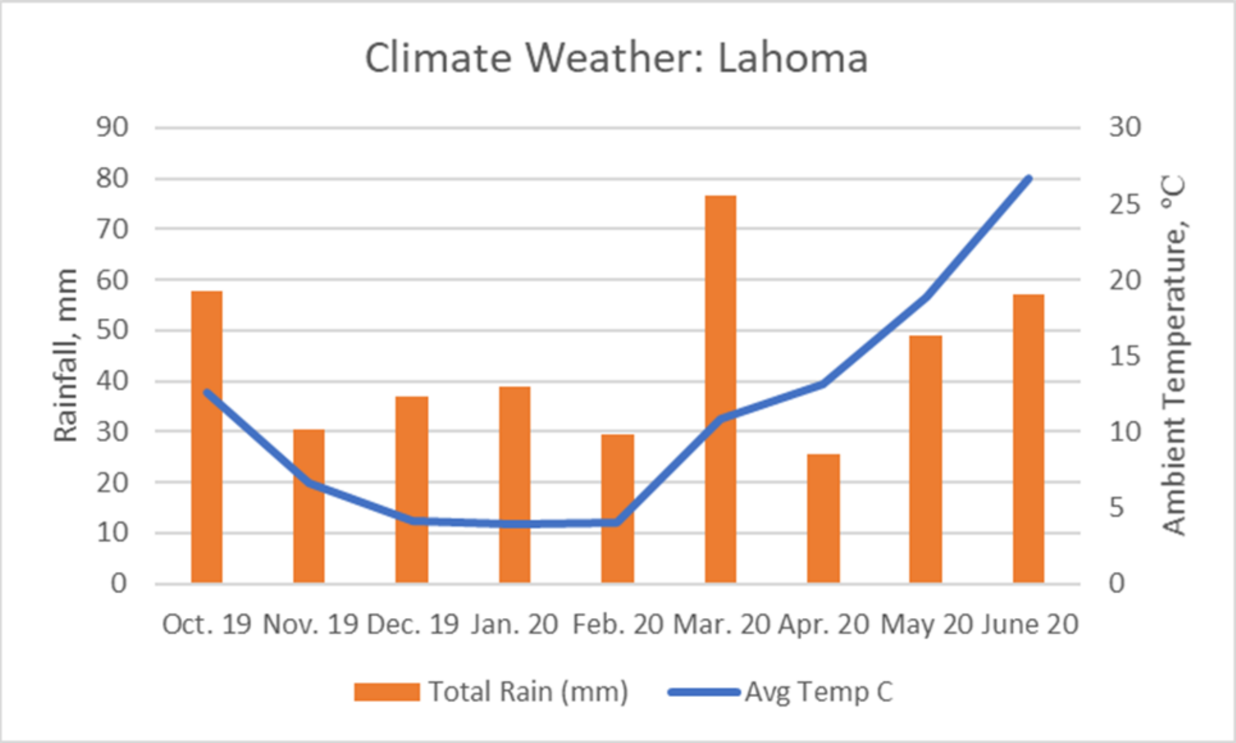

Figure 6.) Average temperature and rainfall by month across the growing season in Lahoma, Oklahoma 2019-2020.

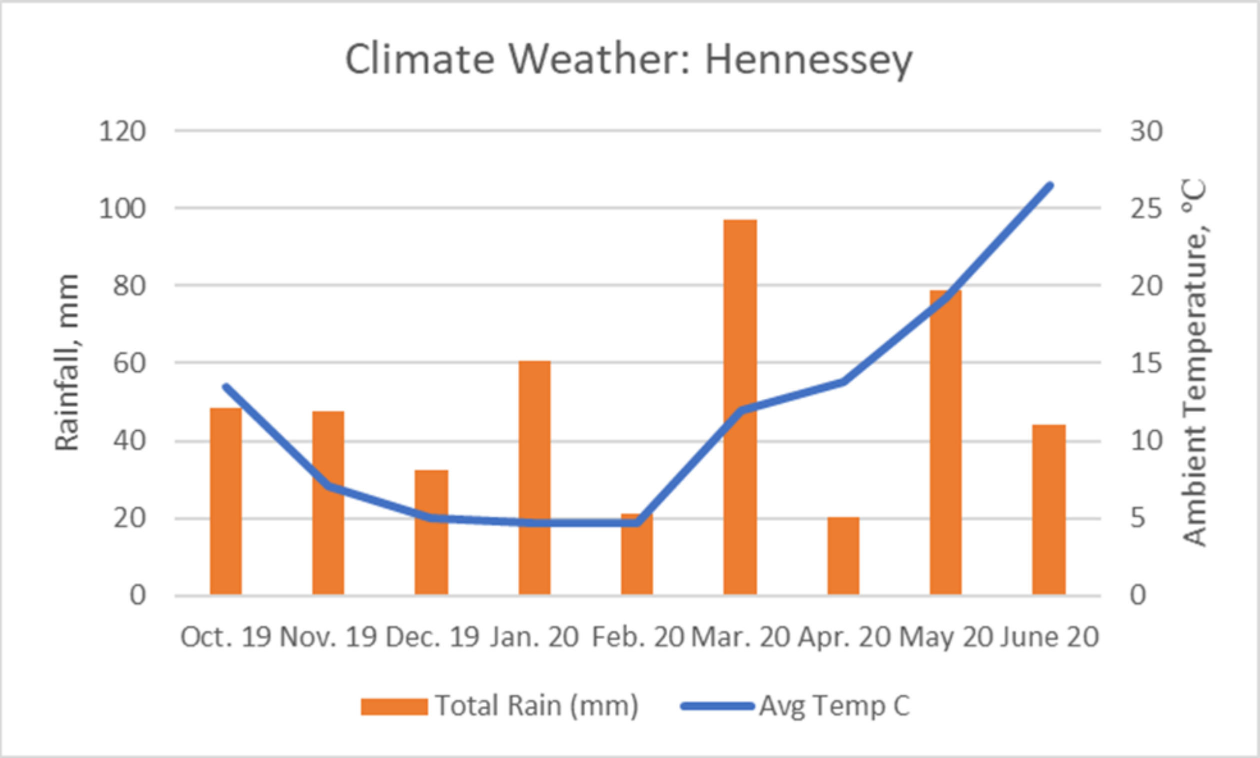

Figure 7.) Average temperature and rainfall by month across the growing season in Hennessey, Oklahoma 2019-2020.

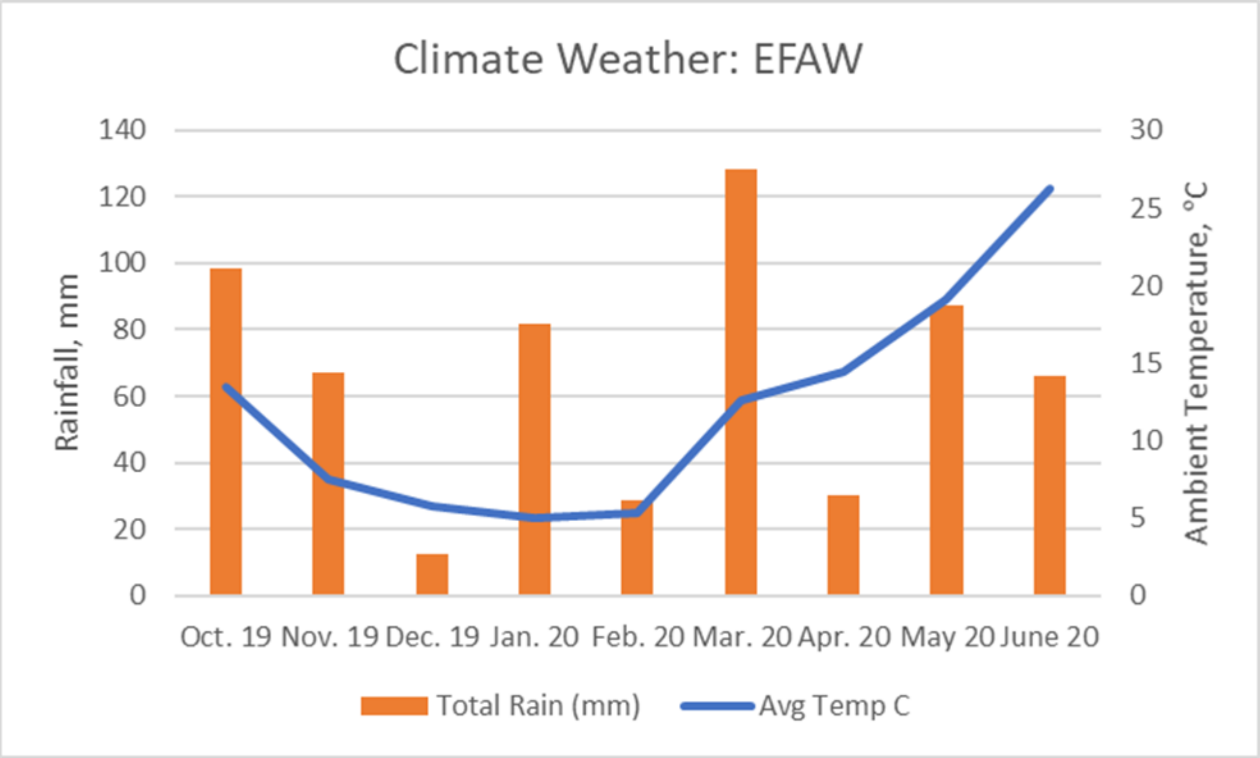

Figure 8.) Average temperature and rainfall by month across the growing season in EFAW, OK 2019-2020.

Figure 9.) Mid-season picture Hennessey OK, 2020.

Figure 10.) Mid-season subsurface application of UAN at Lahoma OK, 2020.

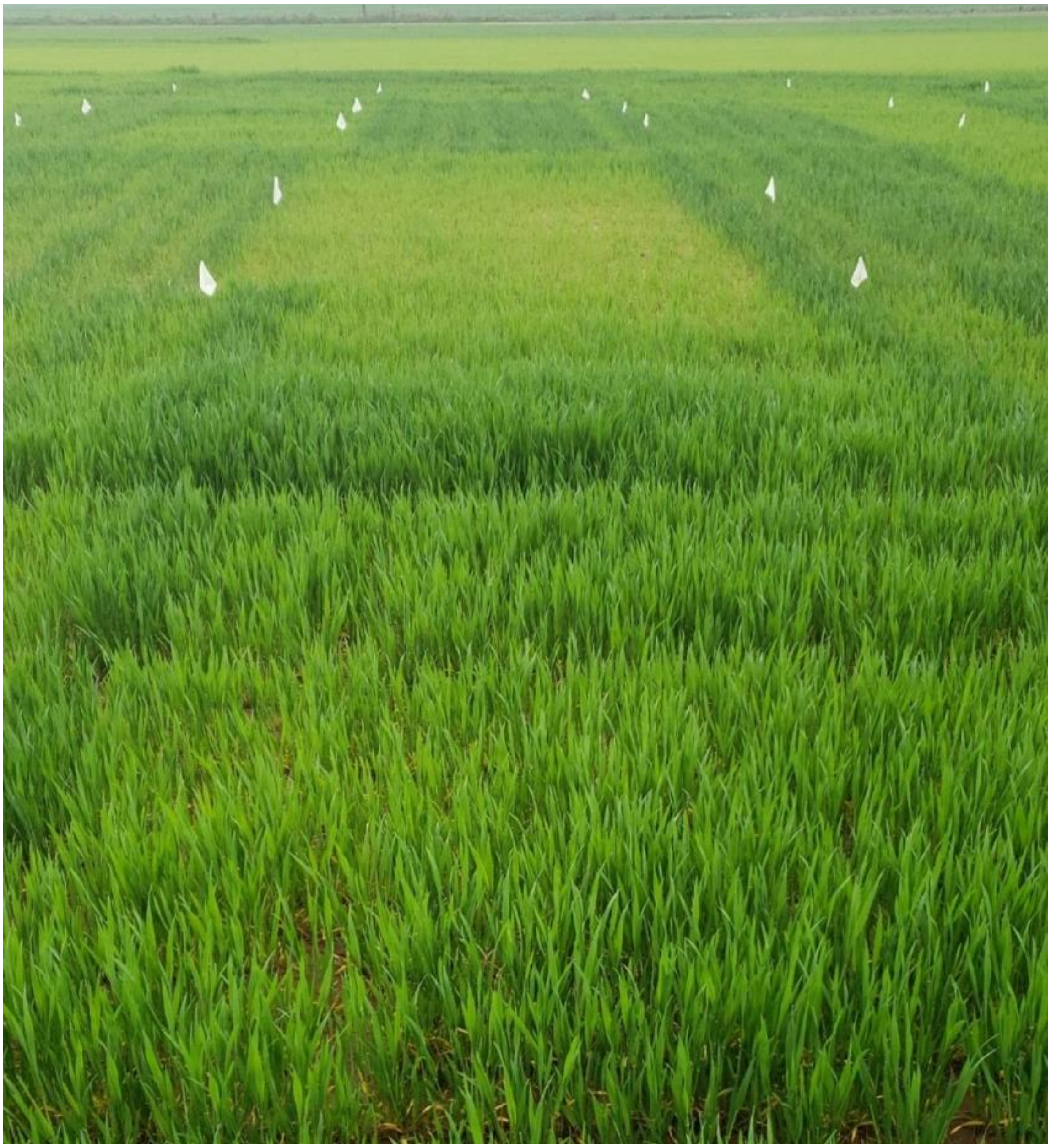

Figure 11.) Mid-season visual N response Lahoma OK, 2020.

VITA

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Master of Science

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