I. OPTIMUM SULFUR APPLICATION FOR SOYBEAN (*Glycine max*) IN OKLAHOMA. II. INFLUENCE OF PREPLANT AND TOPDRESS NITROGEN ON WINTER WHEAT (*Triticum aestivum*) GRAIN YIELD.

By

GWENDOLYN BESS WEHMEYER

Bachelor of Science in Agriculture Business
Northwest Missouri State University
Maryville, Missouri
2015

Master of Science in Plant and Soil Sciences
Oklahoma State University
Stillwater, Oklahoma
2017

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, 2020

I. OPTIMUM SULFUR APPLICATION FOR

SOYBEAN (*Glycine max*) IN OKLAHOMA.

II. INFLUENCE OF PREPLANT AND TOPDRESS

NITROGEN ON WINTER WHEAT (*Triticum aestivum*)

GRAIN YIELD.

Dissertation Approved:

Dr. William Raun

Dissertation Advisor

Dr. Brian Arnall

Dr. Hailin Zhang

Dr. Paul Weckler

Name: GWENDOLYN BESS WEHMEYER

Date of Degree: MAY, 2020

Title of Study: I. OPTIMUM SULFUR APPLICATION FOR SOYBEAN (Glycine max) IN OKLAHOMA.

II. INFLUENCE OF PREPLANT AND TOPDRESS NITROGEN ON WINTER WHEAT (*Triticum aestivum*) GRAIN YIELD

Major Field: SOIL SCIENCE

Abstract: Soybean (Glycine max) are a vital legume crop present in the United States with substantial nutritional value and oil content. In 2017, 36,421,707 ha of soybean were harvested in the US (USDA, 2017). As soybean markets increase and stabilize, input strategies become exceedingly beneficial to further increase yield and monetary oil content potential for producers. Various articles indicate that the addition of sulfur (S) can assist in the synthesis of amino acids and proteins, and also increase nitrogen (N) fixation, further increasing oil content for oilseeds. The objective of this study was to evaluate the effect of S application rate and timing on soybean to further increase oil content and grain protein. The application of fertilizer nitrogen (N) either before planting and/or during the growing season impacts final grain yield differently depending on the environment. Oklahoma State University initiated a long-term winter wheat trial in 2002, to evaluate a combination of preplant and topdress rate on wheat grain yield and N response. This long-term field experiment is located at Lake Carl Blackwell, Oklahoma. Treatments included combinations of all N applied preplant and added sidedress applications in February and March. Total N rates ranged from 0 to 150 kg N ha-1. Preplant N applications were made using ammonium nitrate (34-0-0) (N-P-K). Midseason February and March applications used urea ammonium nitrate (UAN) (28-0-0) as the N source. For all years, winter wheat was planted in October and harvested the following July. From 2002 to 2018, grain yield, nitrogen response, and normalized difference vegetative index (NDVI) were analyzed to decipher the optimum preplant and topdress N combinations that would maximize wheat grain yields, over a wide range of environments (years). It was clear over the ten years where yield data was collected, split N applications resulted in consistently higher yields.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

OPTIMUM SULFUR APPLICATION FOR SOYBEAN (Glycine max) IN OKLAHOMA.

ABSTRACT

Soybean (Glycine max) are a vital legume crop present in the United States with substantial nutritional value and oil content. In 2017, 36,421,707 ha of soybean were harvested in the US (USDA, 2017). As soybean markets increase and stabilize, input strategies become exceedingly beneficial to further increase yield and monetary oil content potential for producers. Various articles indicate that the addition of sulfur (S) can assist in the synthesis of amino acids and proteins, and also increase nitrogen (N) fixation, further increasing oil content for oilseeds.

The objective of this study was to evaluate the effect of S application rate and timing on soybean to further increase oil content and grain protein. Four field experiments in 2017, three field experiments in 2018, and one field experiment in 2019 were used. All trials in 2017 were double crop soybean, following winter wheat harvest and under no-tillage. Two trials in 2018 were full season soybean (LCB and Perkins north), while one was double crop (Perkins south), and all under conventional tillage. In 2019, a double crop soybean trial was planted in a conventional-tillage setting.

In 2017, field trials located in Garber, OK were planted at 210,000 seeds per ha^{-1} at a row spacing of 762mm and field trials in Lamont, OK were planted at 210,700 seeds ha^{-1} with a row spacing of 381mm.

In 2018, LCB and Perkins north were planted at 232,180 seeds ha^{-1}, while Perkins south was planted at 316,160 seeds ha^{-1}. In 2019, LCB was planted at 316,160 seeds ha^{-1}. All field experiments were conducted within the state of Oklahoma.

Treatments included a zero-N-check and zero-S-check with no N or S, in addition to S and N preplant and sidedress applications ranging anywhere from 5 to 14 kg ha^{-1} of actual S and N, respectively. Preplant soil samples were taken from both surface and subsurface prior to preplant N and S applications. Ammonium nitrate was used for both preplant and sidedress applications of N and ammonium sulfate for S applications. Research concluded that the addition of S had little to no benefit relative to increasing oil and protein content in soybean. In some cases, the addition of S has decreased yields, especially when the soil was 100% sufficient prior to seasonal S application.

INTRODUCTION

Soybeans are known to be the second largest crop grown in the United States (Soy Grown in the USA, 2017). Soybeans are known for their high protein and oil content. They contain high sources of calcium (Ca) and phosphorus (P), which include vitamins A, B, C, and D (Farhad et al., 2010). Within a protein and oil-based soybean, high quality protein is present, anywhere between 420-450 g kg^{-1} and edible oil nearly 200-220 g kg^{-1} (Farhad et al., 2010).

In 2016, the United States produced 117 million metric tons of soybean (U.S. Yield & Production: Production History, 2017). In addition, the average yield for that year was 3.05 Mg ha^{-1} (White, 2017). Soybeans are a vital crop, not just for their legume characteristics, but for their oilseed, as well. Soybeans represent 61% of the total oilseed production in the world (2016 Soy Highlights, 2017).

In 2016, the United States produced 10.2 million metric tons of soybean oil, while being the consumer for 9.3 million metric tons. Overall, 54% of the total U.S. oil consumption comes from soybean production. In 2016, 196 thousand hectares were planted to soybeans in Oklahoma, with an average yield of two metric tons per hectare (U.S. Planting Data: Soybean Area Planted by State, 2017). Soybean value is increasing, as consumers are searching food labels that are clean and specified to diet recommendations. Furthermore, consumers are more likely to purchase soybean oil, by nearly 87% due to increased health benefits. Retailers and manufacturers are noticing percent sale increases, when food-based products contain 100% US-grown soybean. Additionally, consumers are 75% more likely to purchase their vegetable oil, if the label states that it is 100% US-grown soybean oil (Soy Grown in the USA, 2017).

Soybeans are well-known for their unique and versatile chemical make-up, making them a valuable commodity. Mature soybeans are broken down into 5 categories, such as protein at 350 g kg^{-1}, oil at 190 g kg^{-1}, insoluble carbohydrates at 150 g kg^{-1}, soluble carbohydrates at 15 g kg^{-1}, and moisture ash and other at 130 g kg^{-1} (Wykes, 2018). Additionally, soybean contain isoflavones, which are known for the powerful ability to prevent human cancers and other diseases (Messina et al., 1994).

Grain yield will continuously be the number one focus for producers, when searching for seed varieties, but since the early 2000's, the importance of oil content in soybean has been a striking key factor for producers. In 2001, various elevators began distributing oil premiums to producers who met specified oil percentages at crushing plants. When grain reaches an elevator, it is evaluated for foreign material (FM) and grain moisture at levels that are higher than 130 g kg^{-1} (Wykes, 2018). Elevators then sell soybean to crushing plants or processors. Processors evaluate grain for protein, oil, and amino acid levels. Processors will pay elevators or grain producers for the metric tons of soybean that they bring in. The premium that producers receive is based on the quality of the soybean product and what processors are able to produce from that certain load of grain (Ramesh, 2002). Consumer demand levels of protein and oil contents that processors must meet. Maintaining high protein and oil levels is crucial for producers, when it comes to the production of soybean meal. Protein and oil percentages drive the market and demand for soybeans, which increases profitability for producers. Ag Processing Inc (AGP), the third largest soybean crusher in the nation, paid up to 7 and a half cents per bushel at the higher end of a premium sale. Premium sales would begin at 190.6 g kg^{-1} of oil, paying one cent to the producer for every g kg^{-1} of oil above that given level. High-oil premiums can be worth nearly \$8.65 ha^{-1} at yield levels of 3 Mg ha^{-1} (Hest, 2001).

Sulfur is a mineral and micronutrient that is essential for plant life (Schnug et al., 2005). Sulfur is considered a secondary nutrient, together with calcium (Ca) and magnesium (Mg) (Davidson, 2014). Of the 17 essential elements for plant growth, S ranks 13th for its abundancy (Tisdale et al., 1975).

It is an ample element of the earth's crust that is commonly removed from volcanic deposits and salt domes. Sulfur is vital for the growth of various plants due to its synthesizing characteristics in coenzyme A, biotin, thiamin, vitamin B, and glutathione (Farhad et al., 2010). Sulfur is an essential building block in chlorophyll development (Haun, 2018). Sulfur plays an important role in protein synthesis and is a component of amino acids, proteins, and peptides (Davidson, 2014). Cysteine, cysteine, and methionine are essential amino acids containing S, playing critical roles in the chemical make-up of a soybean. Having proper S concentrations in the soil prior to planting, is critical. Concentrations that meet 2.7 to 4.5 kg ha^{-1} of SO4-2 are adequate for plant growth. Sulfur deficient soils will range anywhere between 4.5 and 9 5 kg ha^{-1} and typically lower than 4.5 to 5 kg ha^{-1} in sandy soils (Tisdale et al., 1975).

Research was conducted by Suman et al. (2018), looking at the addition of S and phosphorus (P) in soybean. They noted an increase in oil by 2.3 to 4.8 g kg^{-1} when 10 to 20 kg S ha^{-1} was applied. Suman et al. (2018) also stated that an increase in oil content with S application was potentially due to the assistance of oil synthesis from S by enhancing the level of thioglucosides. Former research from Majumdar et al., (2001) and Kumar et al., (2009) also noted and increase in protein and oil content due to P and S applications. Consequently, the question was, can the addition of S at various rates, further increase protein and oil content in soybean?

OBJECTIVE

The objective of this study was to evaluate the effect of S application rate and timing on soybean to further increase oil content and grain protein.

MATERIALS AND METHODS

In order to evaluate the effects of S applications in double crop and full season soybean, multiple experiments were established. In 2017, four locations were included for the growth of double crop soybean, following wheat harvest (Table 1.1). Three locations were included in 2018, two full season soybean trials and one double crop trial (Table 1.2). One location of double crop soybean was evaluated in 2019 (Table 1.3). All trials were within the state of Oklahoma.

Oklahoma, two near Garber (Mr. Tyler Schnaithman) and two in Lamont (Mr. Brad Griffin) in 2017, one at Lake Carl Blackwell (LCB) and two at Perkins in 2018, followed by one in Perkins in 2019. A randomized complete block design (RCBD) with 9 treatments and four replications was used for all experimental studies, with 3 by 6 m plots and a 3 m alley between each replication (Table 1.4). Treatments included zero-N-check and zero-S-check with no N or S, in addition to S and N preplant and sidedress applications ranging anywhere between 5 and 14 kg ha^{-1} of actual S and N (Table 1.4). Preplant soil samples were taken both surface and subsurface prior to preplant N and S applications (Table 1.7- Table 1.14). Ammonium nitrate (AN) was used for both preplant and sidedress applications of N and ammonium sulfate (AS) for S applications for this study.

For all trials, commercial pesticides were used to minimize plant and/or yield loss from insect(s) and weed(s). In 2017, field trials located in Garber, OK planted at 210,000 seeds ha^{-1} and 210,700 seeds ha^{-1} for trials located in Lamont, OK (Table 1.1).

In 2018, LCB and Perkins north were planted at 232,180 seeds ha^{-1}, while Perkins south was planted at 316,160 seeds ha^{-1} (Table 1.2). In 2019, LCB was planted at 316,160 seeds ha^{-1} (Table 1.3). All locations were harvested with a Kincaid 8XP self-propelled combine. Grain yields were collected at harvest, subsampled, and analyzed for yield and total protein and oil with Near-infrared (NIR) instrumentation.

RESULTS AND DISCUSSION

2017

Garber north

For the 2017 trial at Garber, yield differences were small (Table 1.15). This was consistent when observing the treatment means for oil at this site. For the most part, the only variable that showed a significant treatment difference was protein. This was reflected in finding somewhat higher values in grain protein for the check plot where no N was applied (Table 1.15). This was also found in similar studies conducted by Terman et al. (1969), who found a significant inverse relationship between protein and yield in winter wheat.

Average soybean yields in Oklahoma are roughly 1.8 Mg ha^{-1}, requiring 8.1 kg ha^{-1} of S. In order for a producer to meet a soybean yield goal of 3.5 Mg ha^{-1}, 16.2 kg ha^{-1} of S is required (Table 1.6) (Zhang et al., 2017). As noted in Table 1.7, preplant soil test SO4-S levels were 100% sufficient thus no fertilizer S would be recommended nor would a response be likely.

As a result of applying excess S, yields may well have been reduced via potential acidification of the soil at this location.

Contrast three was significantly different at the 0.10 alpha level, further indicating that AN applied sidedress did increase yields, as AN was applied during the peak for N plant uptake. A robust inverse relationship between protein and oil was seen at this location (Figure 1.1).

Garber south

For the 2017 trial at Garber, yield differences were minor. This was consistent when observing the treatment means for protein at this site. The only variable that showed significant differences as a function of treatment was oil (Table 1.16). Changes in dependent variables evaluated, could be due to a change in soil texture from a silt loam to a silty clay noted beneath the experimental site. An inverse relationship between protein and oil was also seen at this location (Figure 1.2).

Lamont east

For the 2017 trial at Lamont, yield differences were limited. This was further consistent when observing the treatment means for protein and oil at this site (Table 1.17). It was noted that the highest yields (treatment 2 and 7), resulted in the highest oil concentration. This further showed the significant inverse correlation between oil and protein (Figure 1.3). As concentration of one element increases, it can further reduce the concentration of another element in grain quality (Lee et al., 2019).

Lamont west

For the 2017 trial at Lamont, yield differences were small. This followed a similar trend when observing treatment means for protein and oil at this site (Table 1.18).

It was yet again noted that our highest yields (treatments 1, 4, 7, 8, and 9), resulted in highest oil concentration. This further showed the significant inverse correlation between oil and protein (Figure 1.4).

2018

Lake Carl Blackwell

For the 2018 trial at LCB, yield differences were yet again minimal. This was also further consistent for treatment means for both protein and oil at this site (Table 1.19). Contrast four was significantly different at the 0.05 significance level, resulting in higher oil content and yield, when AS was applied sidedress (Table 1.19). Response displayed an inverse relationship between oil and protein (Figure 1.5). Significance was likely less, due to poor grain quality from pot and stem rot, during the late reproductive stage.

Perkins north

For the 2018 trial at Perkins, yield differences were minimal. Low soybean yields were noted, due to deer damage at the reproductive stage (Table 1.20). Protein and oil were both significant at the 0.01 and 0.05 percent significance level. Initial soil test S levels were low (Table 1.12), contributing to increasing protein and oil levels. Oil concentration did increase when AN was applied preplant. Contrast four was significantly different at the 0.01 significance level, resulting in higher oil content when AS was applied sidedress (Table 1.20). Data yet again displayed an inverse correlation between oil and protein (Figure 1.6). Treatment differences were more difficult to detect, due to lower grain yields and quality following deer damage.

Perkins south

For the 2018 trial at Perkins, yield differences were limited. This was consistent for both protein and oil at this site (Table 1.21). Data yet again displayed an inverse relationship between oil and protein (Figure 1.7). During this growing season, minimal rainfall was present in July, causing a potential decrease in oil content (Table 1.5). When drought occurs later in the growing season, protein increases, resulting in lower oil content (United Soybean Board, 2019). Also, stink bugs (Halyomorpha halys) were present during the reproductive stage, potentially impacting grain quality (United Soybean Board, 2019).

2019

Lake Carl Blackwell

For the 2019 trial at LCB, yield differences were small. This was consistent for both protein and oil at this site (Table 1.22). Lake Carl Blackwell, had an early freeze, during the reproductive stage of double crop soybeans, causing a reduction in yield. Added freeze assists in explaining low yield and low grain quality. Results showed a significant inverse relationship between oil and protein (Figure 1.8).

CONCLUSION

For all seven locations from 2017- 2019, applied S did not result in marked differences in grain yield, oil content or grain protein. Soil test S levels were 100% sufficient or close to as much and where treatment differences would not be expected. According to Fenn et al. (2014), annual rainfall can contribute 2.5 to 23.7 kg ha^{-1} of S. The quantities of rainfall received for the 2017, 2018, and 2019 growing seasons, could have potentially reduced response to S for oil content and grain protein. It is critical to note that the addition of S in central OK, was not beneficial as no increase in oil content or grain protein was seen. If producers throughout Oklahoma are questioning a need for S fertilizer, preplant soil samples should be taken to better understand soil test S levels, prior to applying added S at planting.

TABLES AND FIGURES

Table 1. Summary of location, soil type, tillage method, preplant date, planting date, sidedress date, seeding population, and harvest date to evaluate optimum S rate in double crop soybean, 2017, Garber and Lamont, OK.

Location	Soil Type	Tillage Method	Preplant Date	Planting Date	Sidedress Date	Seed Population (seeds ha^{-1})	Seed Variety	Harvest Date
Garber	Kirkland-Renfrow complex	No-tillage	26-Jun-17	6-Jun-17	25-Jul-17	271,700	50T15BR	11-Nov-17
Lamont	Renfrow silty clay loam	No-tillage	26-Jun-17	16-Jun-17	21-Jul-17	271,000	S46XS87	11-Nov-17

Table 2. Summary of location, soil type, tillage method, preplant date, planting date, sidedress date, seeding population, and harvest date to evaluate optimum S rate in full season and double crop soybeans, 2018, Perkins and Lake Carl Blackwell, OK.

Location	Soil Type	Tillage Method	Preplant Date	Planting Date	Sidedress Date	Seed Population (seeds ha^{-1})	Seed Variety	Harvest Date
Perkins	Teller loam	Conventional tillage	10-May-18	10- May-18	18-Jun-18	232,180	P48A60X	30-Oct-18
Perkins	Teller loam	Conventional tillage	29-Jun-18	29-Jun-19	7-Sep-18	316,160	P48A60X	30-Oct-18
Lake Carl Blackwell	Port-Oscar Complex	Conventional tillage	14-May-18	14-May-18	15-Jun-18	232,180	P48A60X	30-Oct-18

Table 3. Summary of location, soil type, tillage method, preplant date, planting date, sidedress date, seeding population, and harvest date to evaluate optimum S rate in double crop soybeans, 2019, Lake Carl Blackwell, OK.

Location	Soil Type	Tillage Method	Preplant Date	Planting Date	Sidedress Date	Seed Population (seeds ha^{-1})	Seed Variety	Harvest Date
Lake Carl Blackwell	Port-Oscar Complex	Conventional tillage	26-Jun-19	26-Jun-19	16-Aug-19	316,160	P48A60X	5-Nov-19

Table 4. Treatment structure, for soybean experiments conducted, at Garber, Lamont, Lake Carl Blackwell, Perkins 2017 and 2018

Treatment	Fertilizer	Timing	kg S ha^{-1}	kg carrier N ha^{-1}	kg total product ha^{-1}
1	check		0	0	0
2	Ammonium Nitrate	Preplant	0	22.4	68
3	Ammonium Nitrate	Sidedress	0	22.4	68
4	Ammonium Sulfate	Preplant	5.5	4.8	23
5	Ammonium Sulfate	Preplant	10.8	9.4	45
6	Ammonium Sulfate	Preplant	16.3	14.3	68
7	Ammonium Sulfate	Sidedress	5.5	4.8	23
8	Ammonium Sulfate	Sidedress	10.8	9.4	45
9	Ammonium Sulfate	Sidedress	16.3	14.3	68

Table 5. Total monthly and seasonal rainfall for 2017, 2018, and 2019, OK.

Location	Year	May Rainfall (mm)	June Rainfall (mm)	July Rainfall (mm)	August Rainfall (mm)	September Rainfall (mm)	October Rainfall (mm)	November Rainfall (mm)	Annual Rainfall (mm)
Garber	2017	63.5	59.2	84.6	135.6	86.4	93.2	3.8	819.9
Lamont	2017	90.9	79.0	63.5	112.8	90.2	68.8	15.5	829.8
Lake Carl Blackwell	2018	75.7	214.9	71.4	151.1	70.6	181.6	11.7	997.2
Perkins	2018	99.6	145.0	64.5	100.3	169.2	122.7	19.8	990.9
Lake Carl Blackwell	2019	413.5	102.6	33.3	208.0	163.6	53.6	58.7	1327.2

Table 6. Sulfur requirement for soybeans.

yield goal Mg ha^{-1}	S kg ha^{-1}
0.6	2.7
1.2	5.4
1.8	8.1
2.3	10.8
2.9	13.5
3.5	16.2

(Zhang et al., 2017)

Table 7. Initial soil test levels prior to treatment application, surface (0-15cm) and subsurface (15- 46cm), Garber north, OK, 2017.

	Surface (0-15cm)					Subsurface (15- 46cm)				
Replication	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}
1	5.0	1.9	4.2	30.9	1.2	6.0	2.0	2.0	17.2	0.8
2	5.2	3.1	4.3	27.9	1.2	5.7	2.9	2.5	21.2	0.9
3	5.2	2.7	3.4	40.0	1.3	5.8	2.0	2.1	19.9	0.8
4	5.0	2.0	3.7	30.1	1.3	6.0	2.3	2.3	17.6	0.9

All values represent the average of 15 cores that were taken from each replication.

Table 8. Initial soil test levels prior to treatment application, surface (0-15cm) and subsurface (15- 46cm), Garber south, OK, 2017.

	Surface (0-15cm)					Subsurface (15- 46cm)				
Replication	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}
1	5.7	4.7	2.6	17.1	1.2	6.2	2.1	2.1	10.9	0.9
2	5.9	4.4	2.2	18.0	1.2	5.9	2.0	1.5	11.8	0.9
3	6.1	1.6	2.9	20.2	1.4	5.7	2.6	1.9	12.9	0.9
4	5.7	6.7	2.7	20.9	1.3	5.7	2.7	2.1	13.7	0.9

All values represent the average of 15 cores that were taken from each replication.

Table 9. Initial soil test levels prior to treatment application, surface (0-15cm) and subsurface (15- 46cm), Lamont east, OK, 2017.

	Surface (0-15cm)					Subsurface (15- 46cm)				
Replication	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}
1	6.2	1.2	1.8	15.5	1.1	6.8	1.5	3.6	11.4	0.8
2	6.2	1.2	2.0	16.6	1.1	6.5	1.4	3.5	12.2	0.8
3	6.3	1.3	1.9	17.0	1.1	6.4	2.0	3.3	11.6	0.7
4	6.2	2.4	2.3	13.5	1.0	6.3	1.5	3.5	11.1	0.8

All values represent the average of 15 cores that were taken from each replication.

Table 10. Initial soil test levels prior to treatment application, surface (0-15cm) and subsurface (15- 46cm), Lamont west, OK, 2017.

	Surface (0-15cm)					Subsurface (15- 46cm)				
Replication	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}
1	6.5	0.8	1.7	18.7	1.1	7.6	2.5	3.1	13.4	0.8
2	6.2	0.9	1.6	14.9	1.1	7.6	4.0	2.5	13.2	0.7
3	6.2	0.7	1.5	15.7	0.9	7.6	3.5	3.2	15.3	0.7
4	6.4	1.0	2.1	13.3	1.0	7.6	2.7	2.5	15.9	0.8

All values represent the average of 15 cores that were taken from each replication.

Table 11. Initial soil test levels prior to treatment application, surface (0-15cm) and subsurface (15- 46cm), Lake Carl Blackwell, OK, 2018.

	Surface (0-15cm)					Subsurface (15- 46cm)				
Replication	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}
1	6.2	8.4	25.6	9.4	13.0	6.4	12.8	14.9	8.1	6.9
2	6.2	11.3	16.5	7.7	8.7	6.5	13.6	14.3	5.0	7.4
3	6.1	14.1	18.5	9.4	8.3	6.7	18.9	14.1	6.8	8.1
4	6.8	10.1	13.0	5.2	8.2	6.4	6.5	21.2	7.4	9.3

All values represent the average of 15 cores that were taken from each replication.

Table 12. Initial soil test levels prior to treatment application, surface (0-15cm) and subsurface (15- 46cm), Perkins north, OK, 2018.

	Surface (0-15cm)					Subsurface (15- 46cm)				
Replication	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}
1	6.2	1.9	94.4	7.5	9.9	6.9	2.4	64.0	5.3	10.0
2	6.1	1.9	104.6	6.8	12.1	6.8	2.3	39.7	5.1	12.1
3	5.9	1.5	60.2	7.7	11.2	6.8	2.4	74.1	5.5	12.1
4	6.0	1.1	47.9	8.0	9.6	6.9	2.0	75.1	5.9	11.1

All values represent the average of 15 cores that were taken from each replication.

Table 13. Initial soil test levels prior to treatment application, surface (0-15cm) and subsurface (15- 46cm), Perkins south, OK, 2018.

	Surface (0-15cm)					Subsurface (15- 46cm)				
Replication	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}
1	5.8	13.1	20.6	6.3	8.3	6.2	7.1	13.0	6.4	7.9
2	5.6	13.1	14.8	7.6	8.3	6.0	8.9	17.4	9.2	9.2
3	5.8	12.4	14.1	8.4	8.6	6.2	11.0	19.9	8.7	8.1
4	5.8	13.2	14.7	5.6	9.2	6.3	11.4	13.8	8.4	8.5

All values represent the average of 15 cores that were taken from each replication.

Table 14. Initial soil test levels prior to treatment application, surface (0-15cm) and subsurface (15- 46cm), Lake Carl Blackwell, OK, 2019.

	Surface (0-15cm)					Subsurface (15- 46cm)				
Replication	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}	pH	NO_3-N, kg ha^{-1}	NH_4-N, kg ha^{-1}	SO_4-S, kg ha^{-1}	Organic Carbon, g kg^{-1}
1	5.4	6.7	21.5	22.4	10.4	6.2	4.5	17.5	13.4	10.4
2	5.7	4.5	19.9	20.2	10.0	6.2	4.5	16.8	13.4	9.9
3	5.5	4.5	20.8	17.9	10.7	6.1	2.2	16.6	11.2	9.2
4	5.7	4.5	20.8	20.2	10.4	6.5	2.2	16.1	9.0	8.5

All values represent the average of 15 cores that were taken from each replication.

Table 15. Treatment structure, treatment means, and single-degree-of-freedom contrasts for grain yield, oil, and protein for 2017, Garber north, OK.

	Source	Timing	kg S ha^{-1}	carrier N kg ha^{-1}	yield Mg ha^{-1}	oil g kg^{-1}	protein g kg^{-1}
1	check		0	0	0.8 ^{A}	193.1 ^{A}	445.4 ^{A}
2	AN	Pre	0	22.4	0.8 ^{A}	193.3 ^{A}	443.9 ^{BA}
3	AN	Side	0	22.4	0.8 ^{A}	202.4 ^{A}	432.1 ^{B}
4	AS	Pre	5.5	4.8	0.7 ^{A}	195.1 ^{A}	443.1 ^{BA}
5	AS	Pre	10.8	9.4	0.6 ^{A}	196.0 ^{A}	440.9 ^{BA}
6	AS	Pre	16.3	14.3	0.6 ^{A}	194.0 ^{A}	440.3 ^{BA}
7	AS	Side	5.5	4.8	0.7 ^{A}	197.6 ^{A}	438.4 ^{BA}
8	AS	Side	10.8	9.4	0.6 ^{A}	198.5 ^{A}	438.6 ^{BA}
9	AS	Side	16.3	14.3	0.6 ^{A}	200.2 ^{A}	437.4 ^{BA}
SED					0.2	1.3	1.5
TRT					ns	ns	ns
Contrast (Treatments)							
1. AN Preplant (2) vs AS Preplant (6)					ns	ns	ns
2. AN Sidedress (3) vs AS Sidedress (9)					ns	ns	ns
3. AN Preplant (2) vs AN Sidedress (3)					ns	***	***
4. Preplant (4, 5, 6) vs Sidedress (7,8,9)					ns	ns	ns

Means followed by the same letter were not significantly different, alpha= 0.05.
*, **, ***, Significant at the 0.01, 0.05, and 0.10 probability levels, respectively; ns= non-significant.
SED= standard error of the difference between two equally replicated means, AN= ammonium nitrate, AS=ammonium sulfate, PP= preplant, SD=sidedress.

Table 16. Treatment structure, treatment means, and single-degree-of-freedom contrasts for grain yield, oil, and protein for 2017, Garber south, OK.

	Source	Timing	kg S ha^{-1}	carrier N kg ha^{-1}	yield Mg ha^{-1}	oil g kg^{-1}	Protein g kg^{-1}
1	check		0	0	1.4 AB	197.0 AB	439.4 A
2	AN	Pre	0	22.4	1.1 B	189.8 B	446.0 A
3	AN	Side	0	22.4	1.2 AB	192.5 BC	443.8 A
4	AS	Pre	5.5	4.8	1.4 AB	191.7 BC	447.2 A
5	AS	Pre	10.8	9.4	1.3 AB	195.5 ABC	445.7 A
6	AS	Pre	16.3	14.3	1.2 AB	192.9 BC	447.3 A
7	AS	Side	5.5	4.8	1.1 B	195.3 ABC	444.8 A
8	AS	Side	10.8	9.4	1.5 A	201.1 A	439.5 A
9	AS	Side	16.3	14.3	1.2 AB	190.8 BC	445.0 A
SED					0.3	1.1	1.3
TRT					ns	**	Ns
Contrast (Treatments)							
1. AN Preplant (2) vs AS Preplant (6)					ns	ns	Ns
2. AN Sidedress (3) vs AS Sidedress (9)					ns	ns	Ns
3. AN Preplant (2) vs AN Sidedress (3)					ns	ns	Ns
4. Preplant (4, 5, 6) vs Sidedress (7,8,9)					ns	ns	Ns

Means followed by the same letter were not significantly different, alpha= 0.05.

*, **, ***, Significant at the 0.01, 0.05, and 0.10 probability levels, respectively; ns= non-significant.

SED= standard error of the difference between two equally replicated means, AN=ammonium nitrate, AS=ammonium sulfate, PP=preplant, SD=sidedress.

Table 17. Treatment structure, treatment means, and single-degree-of-freedom contrasts for grain yield, oil, and protein for 2017, Lamont east, OK.

	Source	Timing	kg S ha^{-1}	carrier N kg ha^{-1}	yield Mg ha^{-1}	oil g kg^{-1}	protein g kg^{-1}
1	Check		0	0	1.2 ^{A}	144.2 ^{A}	281.1 ^{A}
2	AN	Pre	0	22.4	2.0 ^{A}	210.6 ^{A}	400.3 ^{A}
3	AN	Side	0	22.4	1.7 ^{A}	199.3 ^{A}	418.7 ^{A}
4	AS	Pre	5.5	4.8	1.4^{A}	196.3 ^{A}	421.3 ^{A}
5	AS	Pre	10.8	9.4	0.9 ^{A}	149.7 ^{A}	316.4 ^{A}
6	AS	Pre	16.3	14.3	1.4 ^{A}	205.7 ^{A}	407.6 ^{A}
7	AS	Side	5.5	4.8	1.9 ^{A}	209.8 ^{A}	400.0 ^{A}
8	AS	Side	10.8	9.4	0.9 ^{A}	148.8 ^{A}	318.4 ^{A}
9	AS	Side	16.3	14.3	1.3 ^{A}	200.4 ^{A}	417.2 ^{A}
SED					0.4	3.5	3.6
TRT					ns	ns	ns
Contrast (Treatments)							
1. AN Preplant (2) vs AS Preplant (6)					ns	ns	ns
2. AN Sidedress (3) vs AS Sidedress (9)					ns	ns	ns
3. AN Preplant (2) vs AN Sidedress (3)					ns	ns	ns
4. Preplant (4, 5, 6) vs Sidedress (7,8,9)					ns	ns	ns

Means followed by the same letter were not significantly different, alpha= 0.05.

*, **, ***, Significant at the 0.01, 0.05, and 0.10 probability levels, respectively; ns= non-significant.

SED= standard error of the difference between two equally replicated means, AN=ammonium nitrate, AS=ammonium sulfate, PP=preplant, SD=sidedress.

Table 18. Treatment structure, treatment means, and single-degree-of-freedom contrasts for grain yield, oil, and protein for 2017, Lamont west, OK.

	Source	Timing	kg S ha^{-1}	carrier N kg ha^{-1}	yield Mg ha^{-1}	oil g kg^{-1}	protein g kg^{-1}
1	check		0	0	1.8 ^{A}	218.5 ^{A}	395.7 ^{A}
2	AN	Pre	0	22.4	1.7 ^{A}	216.1 ^{A}	396.4 ^{A}
3	AN	Side	0	22.4	1.5 ^{A}	217.6 ^{A}	392.7 ^{A}
4	AS	Pre	5.5	4.8	1.8 ^{A}	215.5 ^{A}	394.2 ^{A}
5	AS	Pre	10.8	9.4	1.4 ^{A}	213.1 ^{A}	398.9 ^{A}
6	AS	Pre	16.3	14.3	1.6 ^{A}	216.5 ^{A}	394.4 ^{A}
7	AS	Side	5.5	4.8	1.8 ^{A}	218.4 ^{A}	392.8 ^{A}
8	AS	Side	10.8	9.4	1.9 ^{A}	217.7 ^{A}	397.1 ^{A}
9	AS	Side	16.3	14.3	1.8^{A}	216.4 ^{A}	394.0 ^{A}
SED					0.3	1.1	1.4
TRT					ns	ns	ns
Contrast (Treatments)							
1. AN Preplant (2) vs AS Preplant (6)					ns	ns	ns
2. AN Sidedress (3) vs AS Sidedress (9)					ns	ns	ns
3. AN Preplant (2) vs AN Sidedress (3)					ns	ns	ns
4. Preplant (4, 5, 6) vs Sidedress (7,8,9)					ns	ns	ns

Means followed by the same letter were not significantly different, alpha= 0.05.

*, **, ***, Significant at the 0.01, 0.05, and 0.10 probability levels, respectively; ns= non-significant.

SED= standard error of the difference between two equally replicated means, AN=ammonium nitrate, AS=ammonium sulfate, PP= preplant, SD=sidedress.

Table 19. Treatment structure, treatment means, and single-degree-of-freedom contrasts for grain yield, oil, and protein for 2018, Lake Carl Blackwell, OK.

	Source	Timing	kg S ha^{-1}	carrier N kg ha^{-1}	yield Mg ha^{-1}	oil g kg^{-1}	protein g kg^{-1}
1	check		0	0	3.0 ^{AB}	186.5 ^{A}	329.8 ^{A}
2	AN	Pre	0	22.4	3.1 ^{AB}	184.2 ^{AB}	329.7 ^{A}
3	AN	Side	0	22.4	3.4 ^{AB}	181.8 ^{AB}	342.0 ^{A}
4	AS	Pre	5.5	4.8	2.8 ^{B}	176.3 ^{B}	340.1 ^{A}
5	AS	Pre	10.8	9.4	3.2 ^{AB}	180.2 ^{AB}	337.4 ^{A}
6	AS	Pre	16.3	14.3	3.2 ^{AB}	181.5 ^{AB}	337.3 ^{A}
7	AS	Side	5.5	4.8	3.6 ^{A}	183.2 ^{AB}	333.8 ^{A}
8	AS	Side	10.8	9.4	3.2 ^{AB}	185.5 ^{A}	339.3 ^{A}
9	AS	Side	16.3	14.3	3.3 ^{AB}	185.0 ^{A}	334.7 ^{A}
SED					0.4	1.5	1.8
TRT					ns	ns	ns
Contrast (Treatments)							
1. AN Preplant (2) vs AS Preplant (6)					ns	ns	ns
2. AN Sidedress (3) vs AS Sidedress (9)					ns	ns	ns
3. AN Preplant (2) vs AN Sidedress (3)					ns	ns	ns
4. Preplant (4, 5, 6) vs Sidedress (7,8,9)					ns	**	ns

Means followed by the same letter were not significantly different, alpha= 0.05.

*, **, ***, Significant at the 0.01, 0.05, and 0.10 probability levels, respectively; ns= non-significant.

SED= standard error of the difference between two equally replicated means, AN=ammonium nitrate, AS=ammonium sulfate, PP= preplant, SD=sidedress.

Table 20. Treatment structure, treatment means, and single-degree-of-freedom contrasts for grain yield, oil, and protein for 2018, Perkins north, OK.

	Source	Timing	kg S ha^{-1}	carrier N kg ha^{-1}	yield Mg ha^{-1}	oil g kg^{-1}	protein g kg^{-1}
1	check		0	0	1.4 ^{A}	1762 ^{A}	346.4 ^{C}
2	AN	Pre	0	22.4	1.1 ^{A}	172.5 ^{AB}	345.8 ^{C}
3	AN	Side	0	22.4	1.2 ^{A}	166.1 ^{BCD}	351.5 ^{ABC}
4	AS	Pre	5.5	4.8	1.4 ^{A}	168.1 ^{BC}	355.3 A^{B}
5	AS	Pre	10.8	9.4	0.9 ^{A}	166.8 ^{BC}	347.8 ^{BC}
6	AS	Pre	16.3	14.3	0.9 ^{A}	158.8 ^{D}	360.3 ^{A}
7	AS	Side	5.5	4.8	1.1 ^{A}	168.5 ^{BC}	355.9 ^{AB}
8	AS	Side	10.8	9.4	1.0 ^{A}	170.5 ^{ABC}	352.9 ^{ABC}
9	AS	Side	16.3	14.3	1.2 ^{A}	164.6 ^{CD}	352.2 ^{ABC}
SED					0.3	1.2	1.2
TRT					ns	*	**
Contrast (Treatments)							
1. AN Preplant (2) vs AS Preplant (6)					ns	ns	ns
2. AN Sidedress (3) vs AS Sidedress (9)					ns	ns	ns
3. AN Preplant (2) vs AN Sidedress (3)					ns	***	ns
4. Preplant (4, 5, 6) vs Sidedress (7,8,9)					ns	*	*

Means followed by the same letter were not significantly different, alpha= 0.05.

*, **, ***, Significant at the 0.01, 0.05, and 0.10 probability levels, respectively; ns= non-significant.

SED= standard error of the difference between two equally replicated means, AN=ammonium nitrate, AS=ammonium sulfate, PP=preplant, SD=sidedress.

Table 21. Treatment structure, treatment means, and single-degree-of-freedom contrasts for grain yield, oil, and protein for 2018, Perkins south, OK.

	Source	Timing	kg S ha^{-1}	carrier N kg ha^{-1}	yield Mg ha^{-1}	oil g kg^{-1}	protein g kg^{-1}
1	check		0	0	3.3 ^{A}	176.7 ^{AB}	336.0 ^{A}
2	AN	Pre	0	22.4	2.3 ^{A}	176.6 ^{AB}	335.0 ^{A}
3	AN	Side	0	22.4	2.7 ^{A}	177.8 ^{AB}	334.2 ^{A}
4	AS	Pre	5.5	4.8	3.0 ^{A}	176.5 ^{AB}	338.9 ^{A}
5	AS	Pre	10.8	9.4	2.9 ^{A}	178.4 ^{AB}	340.1 ^{A}
6	AS	Pre	16.3	14.3	3.3 ^{A}	179.0 ^{AB}	332.7 ^{A}
7	AS	Side	5.5	4.8	2.7 ^{A}	178.7 ^{AB}	333.3 ^{A}
8	AS	Side	10.8	9.4	3.4 ^{A}	175.0 ^{B}	337.2 ^{A}
9	AS	Side	16.3	14.3	2.7 ^{A}	180.4 ^{A}	334.4 ^{A}
SED					0.4	1.0	1.4
TRT					ns	ns	ns
Contrast (Treatments)							
1. AN Preplant (2) vs AS Preplant (6)					ns	ns	ns
2. AN Sidedress (3) vs AS Sidedress (9)					ns	ns	ns
3. AN Preplant (2) vs AN Sidedress (3)					ns	ns	ns
4. Preplant (4, 5, 6) vs Sidedress (7,8,9)					ns	ns	ns

Means followed by the same letter were not significantly different, alpha= 0.05.

*, **, ***, Significant at the 0.01, 0.05, and 0.10 probability levels, respectively; ns= non-significant.

SED= standard error of the difference between two equally replicated means, AN=ammonium nitrate, AS=ammonium sulfate, PP=preplant, SD=sidedress.

Table 22. Treatment structure, treatment means, and single-degree-of-freedom contrasts for grain yield, oil, and protein for 2019, Lake Carl Blackwell, OK.

	Source	Timing	kg S ha^{-1}	carrier N kg ha^{-1}	yield Mg ha^{-1}	oil g kg^{-1}	protein g kg^{-1}
1	check		0	0	0.5 ^{AB}	170.2 ^{A}	346.7 ^{A}
2	AN	Pre	0	22.4	0.5 ^{AB}	173.8 ^{A}	333.5 ^{A}
3	AN	Side	0	22.4	0.5 ^{AB}	172.0 ^{A}	340.3 ^{A}
4	AS	Pre	5.5	4.8	0.5 ^{B}	172.4 ^{A}	334.0 ^{A}
5	AS	Pre	10.8	9.4	0.5 ^{B}	175.5 ^{A}	333.0 ^{A}
6	AS	Pre	16.3	14.3	0.5 ^{B}	170.8 ^{A}	333.5 ^{A}
7	AS	Side	5.5	4.8	0.5 ^{B}	168.3 ^{A}	343.2 ^{A}
8	AS	Side	10.8	9.4	0.7 ^{A}	181.8 ^{A}	328.1 ^{A}
9	AS	Side	16.3	14.3	0.5 ^{B}	168.4 ^{A}	343.8 ^{A}
SED					0.2	1.5	1.8
TRT					ns	ns	ns
Contrast (Treatments)							
1. AN Preplant (2) vs AS Preplant (6)					ns	ns	ns
2. AN Sidedress (3) vs AS Sidedress (9)					ns	ns	ns
3. AN Preplant (2) vs AN Sidedress (3)					ns	ns	ns
4. Preplant (4, 5, 6) vs Sidedress (7,8,9)					ns	ns	ns

Means followed by the same letter were not significantly different, alpha= 0.05.

*, **, ***, Significant at the 0.01, 0.05, and 0.10 probability levels, respectively; ns= non-significant.

SED= standard error of the difference between two equally replicated means, AN=ammonium nitrate, AS=ammonium sulfate, PP=preplant, SD=sidedress.

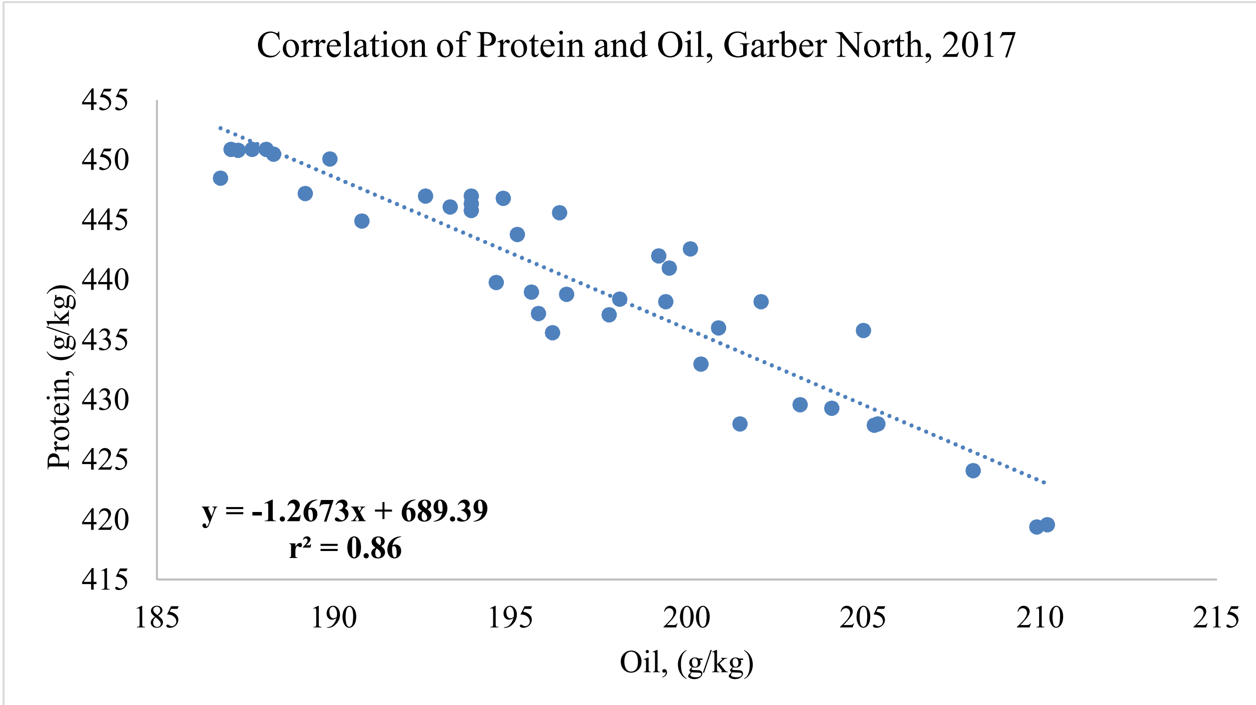

Figure 1. Correlation between protein and oil, Garber north, OK, 2017.

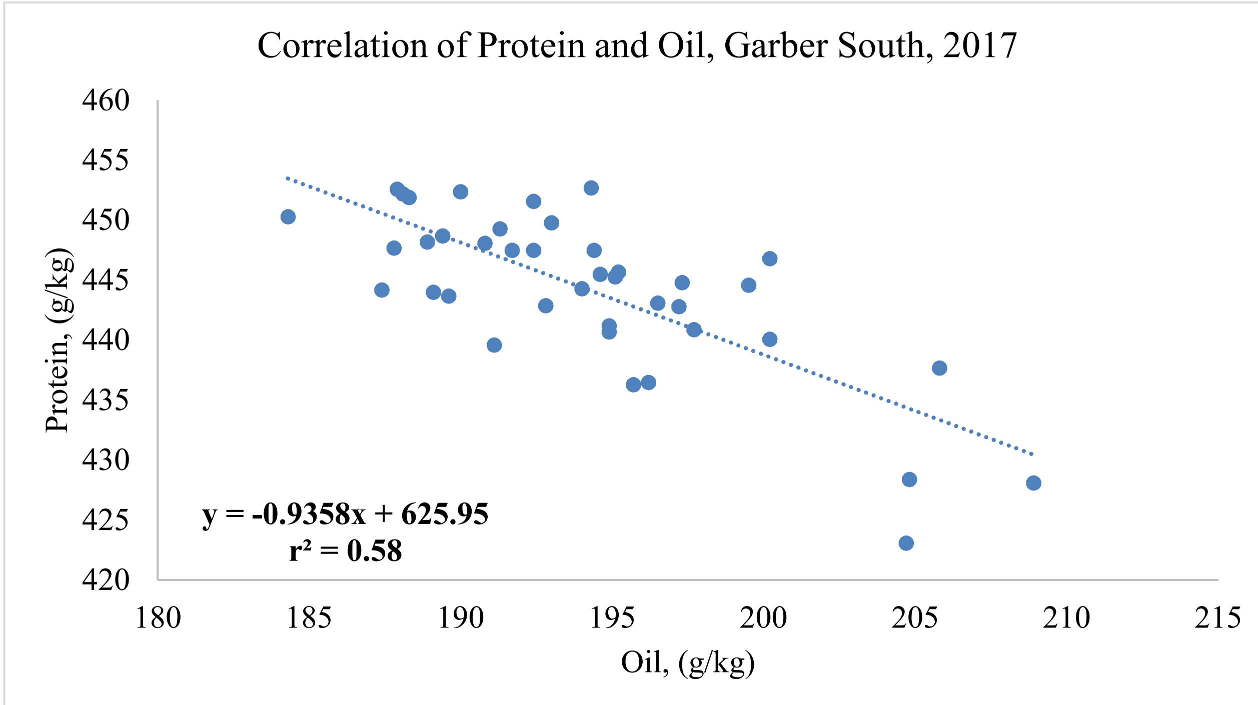

Figure 2. Correlation between protein and oil, Garber south, OK, 2017.

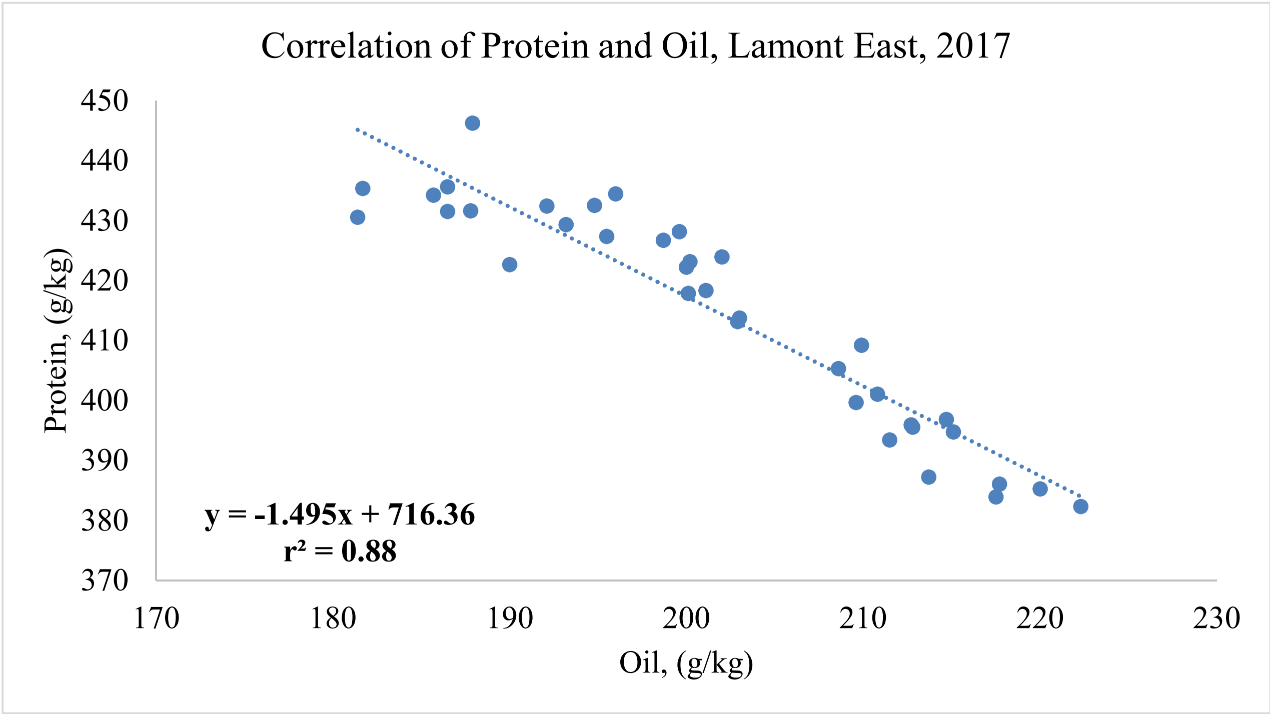

Figure 3. Correlation between protein and oil, Lamont east, OK, 2017.

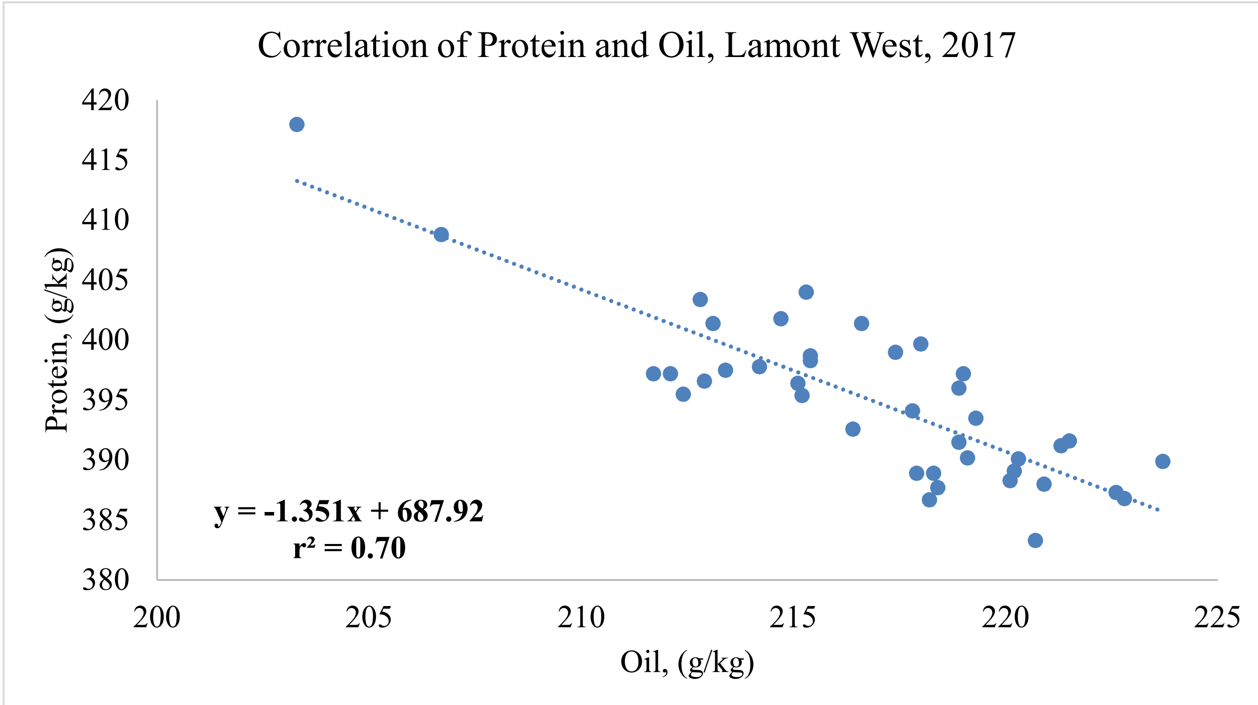

Figure 4. Correlation between protein and oil, Lamont west, OK, 2017.

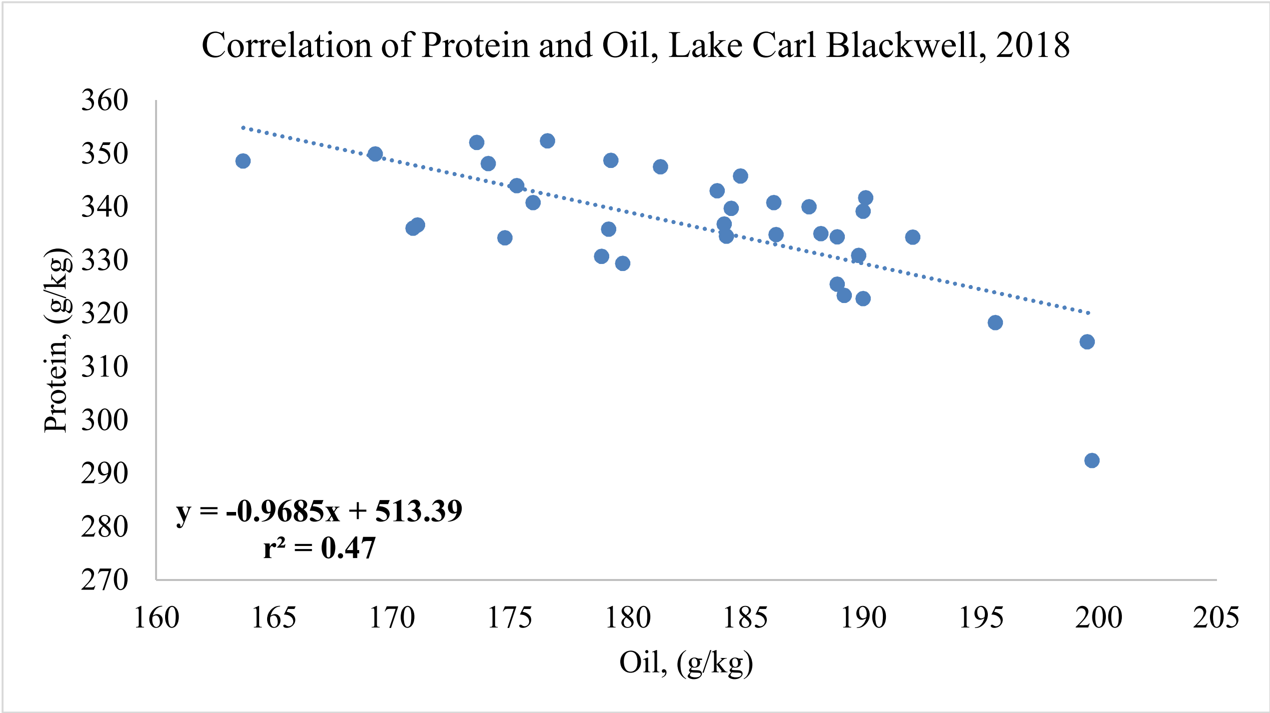

Figure 5. Correlation between protein and oil, Lake Carl Blackwell, OK, 2018.

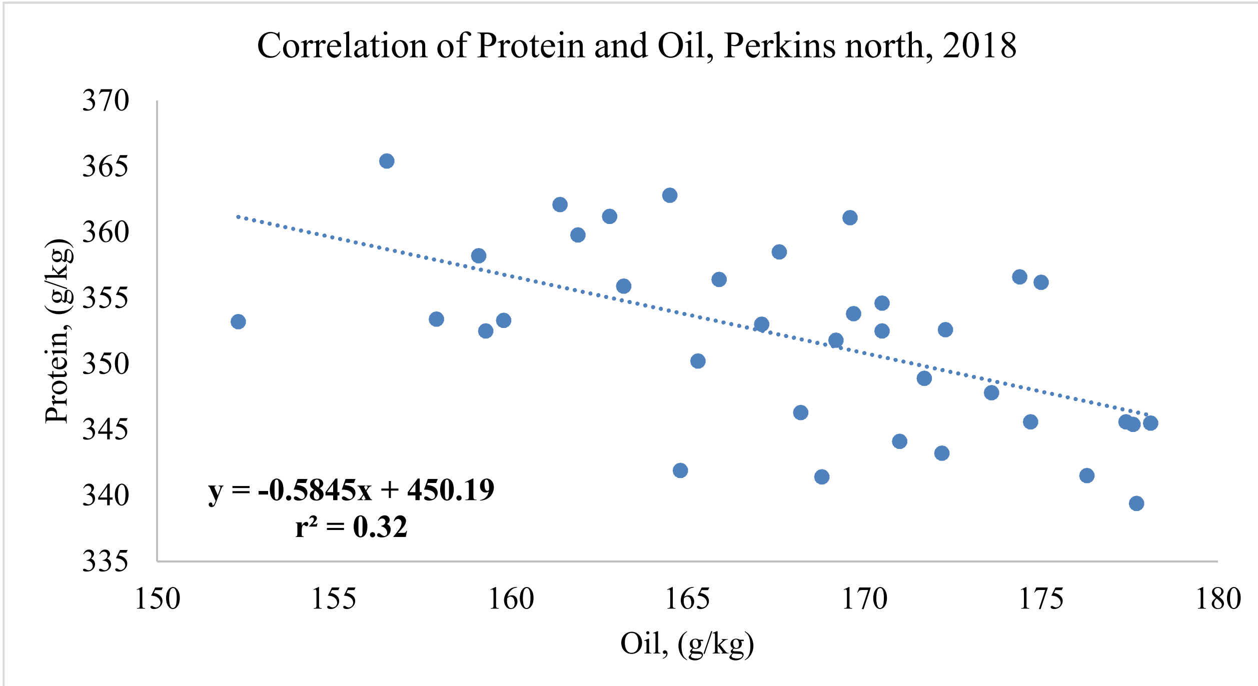

Figure 6. Correlation between protein and oil, Perkins north, OK, 2018.

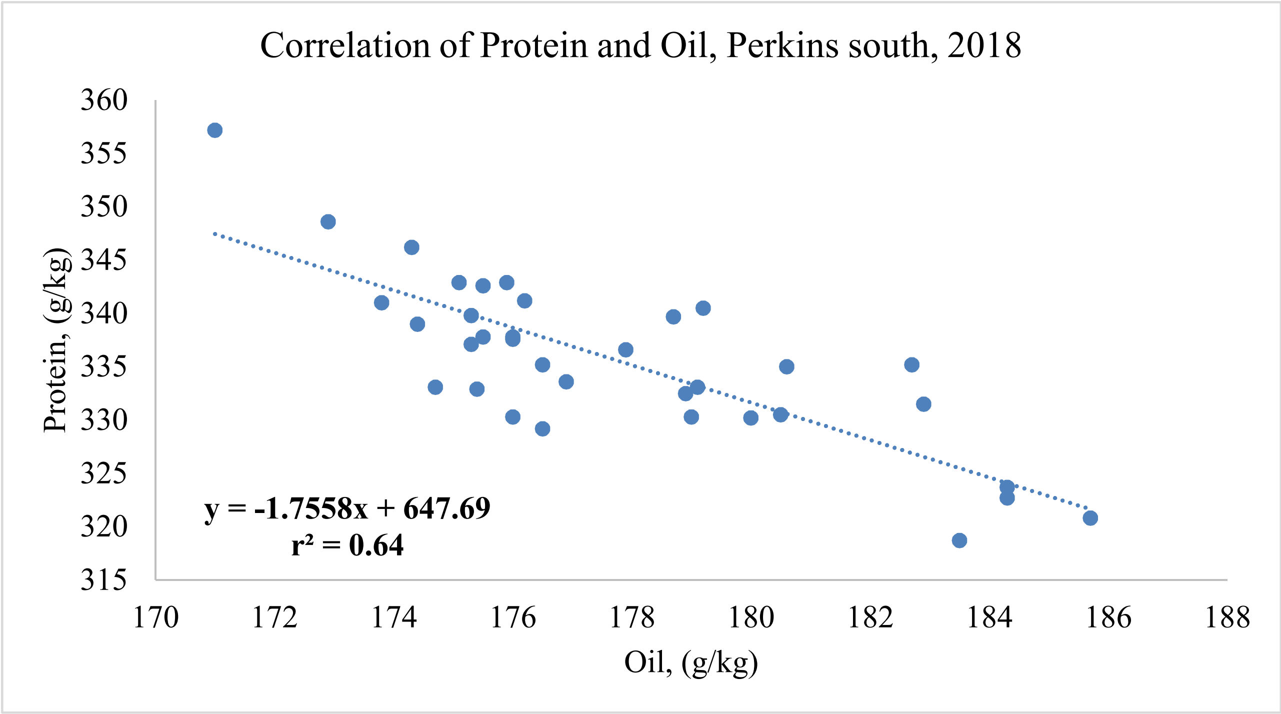

Figure 7. Correlation between protein and oil, Perkins south, OK, 2018.

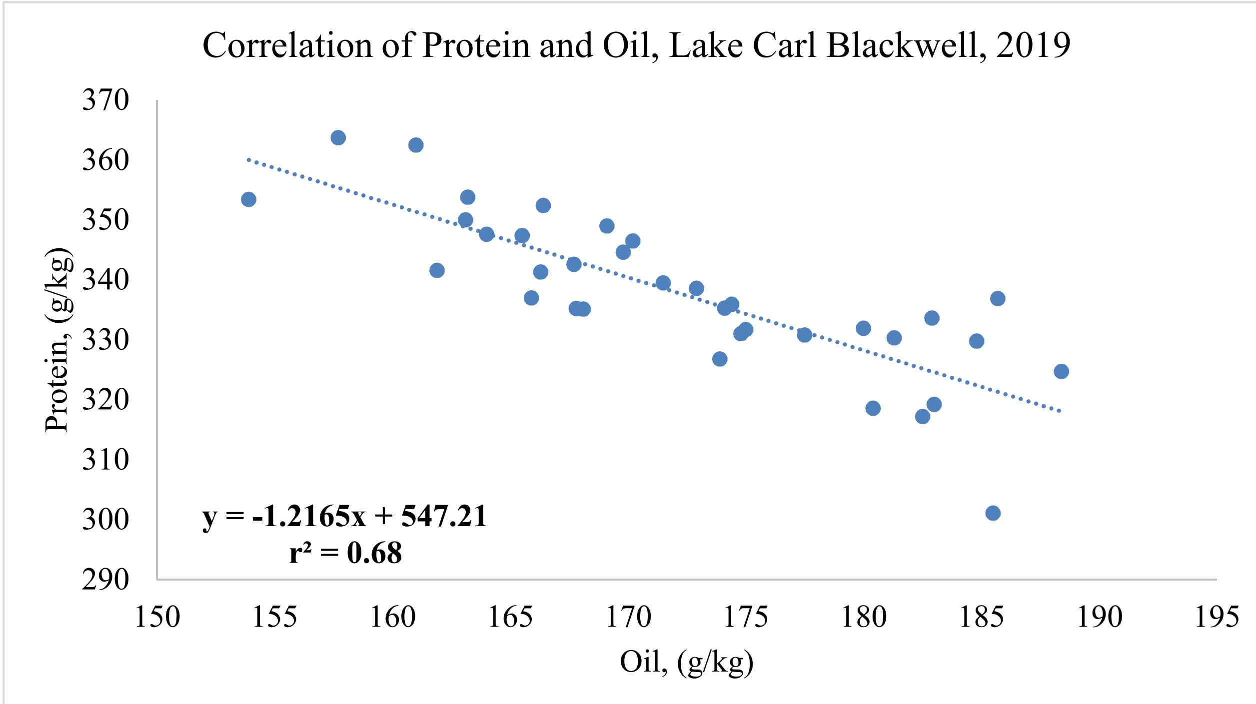

Figure 8. Correlation between protein and oil, Lake Carl Blackwell, OK, 2019.

CHAPTER II

INFLUENCE OF PREPLANT AND TOPDRESS NITROGEN ON WINTER WHEAT (Triticum aestivum) GRAIN YIELD.

ABSTRACT

The application of fertilizer nitrogen (N) either before planting and/or during the growing season impacts final grain yield differently depending on the environment. Oklahoma State University initiated a long-term winter wheat trial in 2002, to evaluate a combination of preplant and topdress rate on wheat grain yield and N response. This long-term field experiment is located at Lake Carl Blackwell, Oklahoma. Treatments included combinations of all N applied preplant and added sidedress applications in February and March. Total N rates ranged from 0 to 150 kg N ha^{-1}. Preplant N applications were made using ammonium nitrate (34-0-0) (N-P-K). Midseason February and March applications used urea ammonium nitrate (UAN) (28-0-0) as the N source. For all years, winter wheat was planted in October and harvested the following July. From 2002 to 2018, grain yield, nitrogen response, and normalized difference vegetative index (NDVI) were analyzed to decipher the optimum preplant and topdress N combinations that would maximize wheat grain yields, over a wide range of environments (years). It was clear over the ten years where yield data was collected, split N applications resulted in consistently higher yields.

INTRODUCTION

Winter wheat is an essential cereal grain crop, providing dietary needs for the developed and developing world. The United States annually consumes 26 million total metric tons of wheat for food purposes, while exporting another 27 million metric tons to other countries (Bond and Liefert, 2017). Work coming from UN DESA, 2015, notes that our world population will increase from 7.3 billion to 9.7 billion, by 2050. Wheat producers are challenged to deliver increased yields via more efficient fertilizer applications and management practices, consistent with the demand for food supplies.

Mohammad et al. (2012), states that N is the most abundant element in the atmosphere. Nitrogen fertilizer is synthetically produced to provide sustainability to plants, increase yield, and improve grain quality (Mohammad et al., 2012). Nitrogen is a primary fertilizer used widely for cereal production, consisting of three main crops; maize (Zea mays), rice (Oryza sativa), and wheat (Triticum aestivum). According to Tilman (1999), global food production has doubled in the past 34 years, increasing N use 6.87-fold.

In 1999, nitrogen use efficiency (NUE) for world cereal crop production was estimated to be 33% (Raun and Johnson, 1999). Even with low NUE, the demand for N fertilizer has increased, with our continual rising world population. If N applications shadow poor management, yields can be affected in a negative manner and environmental pollution increases. Therefore, N research for optimum input, is critical to improve NUE percentages. Research will further increase yield, minimize N loss, and lower input costs. With the assistance of active sensors, various ongoing research projects aim to increase crop NUE (Balcoh et al., 2010; Adam et al., 2008; Raun et al., 2008; Mulvaney et al., 2006). Due to the complexity of the N cycle, soil spatial variability, varying environmental conditions, and correct timing of N remains important (Mohammad et al., 2012).

In order for NUE percentages to increase, accurate management practices for N applications are crucial. Nitrogen losses can occur throughout the growing season, due to environmental factors such as leaching, denitrification, volatilization, and runoff. Nitrate leaching in soil is a concern not only for farmers because of wasted fertilizer dollars, but also for the strict NO3 runoff/leaching regulations (Hubbard et al., 1984; Whitmore and Addiscott, 1986). Furthermore, Omara et al. (2020) noted that losses associated with N could be reduced with adoption of in season variable N application techniques.

Nitrogen plays an important role for producers wanting to reach a certain protein level. Protein content for wheat grain is one of the most vital quality indicators for milling and baking (Mohammad et al., 2012). Protein content in wheat has been adjusted worldwide and producers receive premiums if protein levels are above baseline (Curt et al., 2002). Desired protein levels for wheat, solely depend on the type of wheat and its use (Woolfolk et al., 2002). Various protein percentages are required, based on the variety of wheat. Hard red winter wheat, which is commonly used when making bread, noodles, and animal feed, require higher protein content ranging from 12-16% (Mohammad et al., 2012). Soft red winter wheat requires protein content ranging from 8-11% (Mohammad et al., 2012). Nitrogen is essential for the make-up of protein. With the potential losses known to take place for N, average recovery rates fall in the range of 20 to 50% for grain production systems in winter wheat (Raun and Johnson, 1999). Nitrogen deficiencies that occur throughout the growing season can lead to lower protein quality, thus reducing premium potential for producers (Daigger et al., 1976).

There are commonly two forms of application, when applying N in winter wheat. Producers in the Great Plains will apply all N before planting or apply a small amount in the fall followed by a late winter and/or early spring topdress application, also known as split or triple split applications (Kelly, 1995). Cooper (1974) stated that dry-land wheat receiving N at planting or before head emergence has the potential to increase grain yield but may show little or no effect on grain protein. Although preplant applications of N can reduce deficiencies early in the season, there is potential for negative effects to the environment (Woolfolk et al., 2002).

Mascagni and Sabbe (1991) and Boman et al. (1995) stated, that split application of N (preplant and topdress) are critical when maximizing crop utilization of N and harvested grain yield. Davies et al. (1979) and Ellen and Spiertz (1980) discovered that topdressing N on winter wheat during the spring, resulted in a higher NUE as compared with all-preplant N. Roth and Marshall (1987) stated that yields from split and delayed N were greater than the maximum yield when N applications were all preplant. Alcoz et al., (1993), stated that applying all fertilizer N preplant versus split-applied, had less effect on yield and N parameters. Alcoz et al., (1993), further stated that in 1989, grain yield was significantly increased when split N applications were applied at Feekes growth stages four or six (Large, 1954). Alcoz et al., (1993) also stated, that in 1990, split N application at growth stage 10 increased yield compared with N applied at growth stages 4 or 6. Research from both years, stated that N uptake was the highest when split applications were made (Alcoz et al., 1993). Split applications not only increase yield, but protein as, well. Research shows that protein concentration increases when late N applications are made through foliar or dry topdress applications (Pushman and Bingham, 1976; Westcott, 1998). Recently, research conducted in Oklahoma noted an increase in grain protein concentration, and NUE without decreasing final grain yield with topdress application of N (Dhillon et al., 2020b).

Late-season N applications allow producers to adjust N rates and management based on crop growth for that season (Woolfolk et al., 2002). Late-season applications reduce the chances of N loss, increasing yield and profitability for producers (Woolfolk et al., 2002). Availably of N late in the season when soil moisture is minimal and root uptake is slow, is crucial for increased yield and protein content.

OBJECTIVE

The objective of this study was to evaluate the effect of preplant and topdress N applications in winter wheat on wheat grain yield, and components of yield.

MATERIALS AND METHODS

One experiment was established in 2002 at Lake Carl Blackwell (LCB), Oklahoma, and that is ongoing. Soil for LCB is a Pulaski fine sandy loam, coarse loamy, mixed, superactive, nonacid, Udic Ustifluvent (USDA /NRCS soil taxonomy).

Treatments include rate and time of N fertilizer application in varying combinations (Table 2.1). This experiment was set up in a randomized complete block design of 14 treatments and 4 replications. Different rates of total N applied (0, 45, 90, 135 and 180 kg N ha^{-1}) were applied to evaluate N response. Average temperature and rainfall for each year was analyzed using data from the Oklahoma Mesonet (Table 2.2).

The plot size was 4.86 m by 9.14 m. Urea (45-0-0) was used as the source of N. Phosphorus and potassium fertilizers (P-K) were applied based on soil test results using triple super phosphate (0-0-20) and potassium chloride (0-0-50). Each year, wheat was planted at a seeding rate of 100 kg ha^{-1}. Weeds were controlled using post emergence herbicides. For all years, normalized difference vegetation index (NDVI) sensor readings were collected midseason between 70 and 120 GDD>0. The growing degree days (GDD) metric is mathematically computed as the sum of the number of days from planting to sensing where ((Tmin+ Tmax)/2 – 4.4C) >0, and where Tmin and Tmax are the minimum and maximum daily temperatures, respectively. The NDVI sensor used is manufactured by Trimble Navigation and where NDVI is computed as (NIR-red/NIR+red) where all four values represent the fraction of emitted light for that bandwidth. The NIR and red wavelengths were 780±10 and 671±10 nm, respectively. Sensor NDVI data collected mid-season was used to further evaluate the relationship between these values and final grain yield.

Post-harvest, grain weight and percent moisture was recorded and grain yield (kg ha^{-1}) was calculated. Grain samples were dried and analyzed for total N content using a dry combustion analyzer. Data from 2007, 2008, 2013, 2015, and 2016 were not utilized due to drought or lack of sufficient data. Data from 2003, 2004, 2005, 2006, 2009, 2010, 2011, 2012, 2014, 2017, and 2018 were used for statistical analysis using SAS 9.4, but where NDVI data was not available for all years.

RESULTS AND DISCUSSION

2003, 2004, & 2005

In 2003, split N applications had a significant impact on yield, as opposed to solely one preplant application of N (Figure 2.1). Topdress N application at 45 kg ha^{-1}, had higher yields, in contrast to preplant applied N at 45 kg ha^{-1} (Figure 2.3). Between preplant and topdress rates of 90 kg N ha^{-1} , preplant resulted in increased yield (Figure 2.4). This could have potentially been due to leaching of excess N or maximized plant uptake, therefore minimizing N use efficiency. Kanampiu et al. (2008) noted that uptake efficiency (total shoot N/soil N supply) and utilization (grain yield/total shoot N) of N in the production of grain was essential as it requires accurate processes of uptake, translocation, assimilation, and redistribution of N to operate effectively. Additionally, temperatures were also low from January to March (Table 2.1). Bauer et al. (2017) stated, that N efficiency for plant uptake was minimized when temperature and precipitation were low.

In 2004, single split N was highest for increasing grain yield when 45 kg N ha^{-1} was applied (Figure 2.1). A dramatic increase in response was noted, when comparing the zero-N check and 90 kg ha^{-1}, showing that added N did in fact increased yield (Figure 2.2). Similar results were seen when comparing the zero-N check and a triple split application 45 kg N ha^{-1} preplant (Figure 2.5). When comparing preplant and topdress applications at both 45 kg ha^{-1} and 90 kg ha^{-1}, preplant applications showed a greater yield (Figure 2.3 and 2.4). This could be due to excess rainfall that was seen in the months of March, June, and July (Table 2.2). Applied N could have easily been leached throughout the soil when excess rain occurred, resulting in depleted soil N, during the peak for grain fill (Wise et al., 2011).

In 2005, topdress N applications were reported to increase yield, more-so than preplant applications (Figure 2.1, 2.3, 2.4). Evenly dispersed rainfall and adequate temperatures occurred throughout this year's growing season, and that facilitated the benefits of fertilizer additions when applied in split quantities (Table 2.2).

2006, 2009, & 2010

In 2006, a boost in grain yield was noted in preplant N applications, when comparing preplant and topdress N applications (Figure 2.1, 2.3, 2.4, 2.5). This could be partially explained by increased total rainfall for the month of April (Table 2.2). Nitrogen leaching could have occurred in the soil, and where post topdress N application benefitted from late rainfall. Minimal differences were seen in total grain yield, when looking at preplant and topdress N applications of 45 kg ha^{-1} (Figure 2.1).

In 2009, limited response was shown and where grain yield levels were low. This was likely due to excess rainfall throughout the growing season (Table 2.1).

In 2010, this trial was converted from conventional tillage to no-tillage. Minimal differences were seen between preplant and sidedress applications, relative to yield (Figure 2.1). Rainfall was high throughout the 2010 growing season, especially in the months of October, May, June, and July (Table 2.1). Increased overall yields, could potentially be due to higher seasonal rainfall amounts (Table 2.1).

2011, 2012, & 2014

In 2011, increased temperatures and minimal rainfall, led to drought throughout the winter wheat growing season (Table 2.2). Also, minimal rainfall was recorded in the months of June, July and August, when these lower grain yields were recorded (Table 2.1). Higher yields were seen with topdress N applications, as opposed to preplant (Figure 2.1). Triple split application of 45 kg N ha^{-1} led to higher yields, when compared to the zero-N check (Figure 2.5).

In 2012, a major drought occurred throughout the central great plains, causing economic issues for producers in the agriculture sector. Due to this, grain yield suffered. Even though grain yields were low, differences were detected between preplant and topdress N applications. It was noted that preplant applications were superior overall (Figure 2.1-2.5). This again could be explained by minimal rainfall following topdress N application, causing ammonia volatilization and minimal plant N uptake.

In 2014, an increase in grain yield was noted for preplant N applications, when compared to preplant + topdress N applications (Figure 2.1, 2.3, 2.4, 2.5). This could be explained by minimal precipitation that was seen December through May (Table 2.2). Ammonia volatilization could have occurred, due to the limited rainfall, further minimizing plant N availability. Bacon et al. (1986), noted from research that 35 kg N ha^{-1} can be lost from the soil, in five days when only 8.5mm of rainfall is seen.

2017 & 2018

In 2017 and 2018, similar results were recorded for increasing yields based on preplant and topdress N applications. Both years showed that topdress N was best for increasing overall grain yield (Figure 2.3 and 2.4). Precipitation was evenly distributed throughout the growing season, in addition to having suitable rainfall. This assisted with adequate N use throughout the growing season.

NDVI

Sensor NDVI data was not consistently collected over the many years encumbered in this study. Nonetheless, this does not diminish the value as it still remains important. In 2011, 2012, 2014, NDVI values collected between 74 and 104 GDD>0 did show significant and positive correlation with final grain yield (Table 2.3). Slope components were all highly significant and positive (Figure 2.6, 2.7, 2.8). These findings are consistent with recent work by Dhillon et al., (2020a) who found that the optimum time for collecting sensor readings was when GDD>0 were between 97 and 112. When NDVI was collected within this GDD range, improved prediction of yield was expected.

Added data from other years was available but where numerous issues were encountered and that prevented adequate analysis of this data and the underlying hypothesis that mid-season NDVI should be correlated with final, harvested grain yield.

CONCLUSION

Data collection for various preplant and topdress applications over 15 years clearly notes that environmental conditions are ever changing, leading to inconsistent results for the management practices evaluated. Despite the inconsistent results, mid-season or topdress N applications were on average better than when all N was applied at or near planting.

This work further highlights that it is critical for producers to begin adopting precision agriculture technologies that encumber using mid-season management practices.

Table 23. Treatment structure and winter wheat grain yield, Lake Carl Blackwell, OK 2003-2017.

					Year										
Trt	Preplant N, kg ha^{-1}	February topdress, kg N ha^{-1}	March topdress, kg N ha^{-1}	Total N kg ha^{-1}	2003	2004	2005	2006	2009	2010	2011	2012	2014	2017	2018
										Mg ha^{-1}					
1	0	-	0	0	2.0^{E}	3.5^{G}	2.1^{DC}	2.0^{F}	0.1^{E}	3.0^{A}	1.4^{D}	1.8^{AB}	3.4^{A}	2.5^{D}	2.5^{AB}
2	0	-	45	45	2.9^{DE}	4.0^{FG}	2.6^{ABC}	2.6^{E}	0.1^{E}	2.8^{A}	1.9^{ABC}	2.0^{AB}	3.4^{A}	3.5^{ABC}	2.2^{AB}
3	0	-	90	90	3.0^{CD}	4.7^{CDE}	2.3^{BCD}	3.1^{DE}	0.2^{ABC}	2.7^{A}	2.2^{ABC}	2.3^{AB}	3.9^{A}	3.7^{AB}	2.8^{A}
4	0	-	135	135	3.8^{AB}	5.1^{BCD}	2.1^{DC}	3.8^{C}	0.3^{AB}	2.9^{A}	1.8^{BCD}	2.1^{AB}	3.2^{A}	3.3^{ABC}	2.8^{A}
5	45	-	0	45	0.3^{D}	4.5^{DEF}	2.1^{D}	3.7^{C}	0.0^{E}	2.7^{A}	1.4^{D}	2.3^{AB}	3.8^{A}	3.3^{ABC}	2.2^{AB}
6	45	-	45	90	3.5^{ABC}	5.0^{BCD}	2.7^{AB}	3.9^{C}	0.2^{ABCD}	2.7^{A}	2.1^{ABC}	2.0^{AB}	3.3^{A}	2.9^{DC}	0.7^{B}
7	45	-	90	135	4.1^{A}	5.1^{BCD}	2.9^{A}	4.2^{ABC}	0.2^{BCDE}	2.7^{A}	2.2^{AB}	1.7^{B}	3.7^{A}	3.3^{ABC}	2.4^{AB}
8	45	-	45	90	4.1^{A}	5.3^{BC}	2.6^{ABCD}	4.2^{ABC}	0.2^{BCDE}	2.9^{A}	1.8^{CD}	2.3^{AB}	2.9^{A}	3.9^{A}	3.0^{A}
9	90	-	0	90	3.9^{A}	6.1^{A}	2.1^{DC}	4.6^{A}	0.1^{DE}	3.1^{A}	1.8^{BCD}	2.5^{A}	4.1^{A}	3.7^{AB}	2.1^{AB}
10	90	-	45	135	4.0^{A}	5.0^{BCD}	2.8^{AB}	4.5^{AB}	0.1^{CDE}	3.1^{A}	1.8^{BCD}	2.1^{AB}	3.2^{A}	3.4^{ABC}	3.1^{A}
11	90	-	45	135	3.9^{A}	5.4^{B}	2.4^{ABCD}	4.2^{ABC}	0.4^{A}	3.0^{A}	2.4^{A}	2.1^{AB}	3.7^{A}	3.1^{BCD}	1.9^{AB}
12	90	-	90	180	4.0^{A}	5.5^{AB}	2.2^{BCD}	4.1^{BC}	0.3^{AB}	2.9^{A}	2.0^{ABC}	1.9^{AB}	3.1^{A}	2.9^{CD}	2.4^{AB}
13	45	45	45	135	3.9^{A}	4.9^{BCD}	2.7^{AB}	4.2^{ABC}	0.3^{AB}	2.9^{A}	2.2^{ABC}	1.7^{AB}	3.5^{A}	3.1^{BCD}	2.1^{AB}
14	0	45	45	90	3.3^{BCD}	4.1^{EFG}	2.5^{ABCD}	3.2^{D}	0.2^{BCDE}	2.8^{A}	2.3^{AB}	2.3^{AB}	3.9^{A}	3.5^{ABC}	2.8^{A}
SED					0.3	0.3	0.3	0.2	0.1	0.3	0.2	0.4	0.7	0.4	0.9
TRT					*	*	**	*	*	Ns	*	ns	ns	**	Ns
Contrasts															
Treatment 2 vs 5					ns	***	**	*	ns	ns	**	ns	ns	ns	Ns
Treatment 3 vs 9					ns	*	ns	*	**	ns	***	ns	ns	ns	Ns
Treatment 7 vs 10					ns	ns	ns	ns	ns	ns	***	ns	ns	ns	Ns
Treatment 11 vs 13					ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	Ns

Preplant N linear (Trt; 1, 5, 9)	*	*	ns	*	ns	ns	***	***	ns	*	Ns
Sidedress N linear (Trt; 1, 2, 3, 4)	*	*	ns	*	*	ns	**	ns	ns	**	Ns
Split N linear (Trt; 5, 6, 7)	*	ns	**	***	***	ns	*	ns	ns	ns	Ns
Preplant N quadratic (Trt; 1, 5, 9)	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	Ns
Sidedress N quadratic (Trt; 1, 2, 3, 4)	ns	ns	***	ns	ns	ns	**	ns	ns	***	Ns
Split N quadratic (Trt; 5, 6, 7)	ns	ns	ns	ns	***	ns	ns	ns	ns	ns	**

Means followed by the same letter were not significantly different, alpha= 0.05.

*, **, ***, Significant at the 0.01, 0.05, and 0.10 probabilty levels, respectively; ns= nonsignificant.

Preplant N applied as AN (34-0-0)

Topdress N applied as UAN (28-0-0)

SED= standard error of the difference between two equally replicated means, AN= ammonium nitrate, UAN= urea ammonium nitrate.

Table 24. Total rainfall and average temperature for September through August, Lake Carl Blackwell, OK 2002-19.

	2002-3		2003-4		2004-5		2005-6		2008-9		2009-10		2010-11		2011-12		2013-14		2016-17		2017-18	
Month	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C	Rain, mm	Avg. temp, °C
Sept	105	23	75	20	19	23	90	24	42	21	78	21	71	23	0	21	43	24	65	24	102	23
Oct	83	13	75	16	116	17	48	16	53	15	184	12	44	16	16	16	48	16	98	20	152	16
Nov	6	8	54	10	126	10	0	11	67	9	39	12	49	10	67	10	41	8	22	13	0	11
Dec	71	4	43	6	24	5	2	3	20	3	14	1	14	3	55	4	16	1	10	3	25	4
Jan	2	2	57	3	70	3	18	8	4	2	26	1	8	0	24	5	2	2	65	5	0	2
Feb	24	3	42	4	33	7	2	4	53	8	68	2	48	4	74	6	10	2	56	10	51	4
Mar	79	9	101	12	18	10	47	12	92	12	42	10	21	11	100	16	31	8	49	13	25	11
Apr	35	16	71	16	10	16	131	19	129	15	92	17	50	18	157	18	21	16	253	16	51	12
May	85	20	6	22	98	20	85	22	83	19	181	20	99	20	28	23	17	21	66	20	102	24
Jun	106	23	231	23	97	26	61	26	44	27	139	27	43	29	55	26	160	25	73	6	152	27
Jul	16	29	111	26	82	27	80	10	126	27	112	28	19	32	2	31	101	25	0	28	76	28
Aug	78	9	43	24	223	27	61	29	191	25	64	28	3	31	67	27	51	28	148	25	152	26

Precip- precipitation, measured in mm

Avg. temp- average temperature measured in °C

Table 25. Treatment structure,NDVI, and GDD>0, Lake Carl Blackwell, OK 2011-2014.

					2011		2012		2014	
Trt	Preplant N, kg ha^{-1}	February topdress, kg N ha^{-1}	March topdress, kg N ha^{-1}	Total N kg ha^{-1}	NDVI	GDD > 0	NDVI	GDD > 0	NDVI	GDD > 0
1	0		0	0	0.62^{E}	98	0.70^{DE}	104	0.28^{A}	74
2	0		45	45	0.67^{BCDE}	98	0.68E	104	0.25^{A}	74
3	0		90	90	0.66^{CDE}	98	0.69^{DE}	104	0.26^{A}	74
4	0		135	135	0.68^{ABC}	98	0.71^{CDE}	104	0.26^{A}	74
5	45		0	45	0.63^{DE}	98	0.77^{AB}	104	0.27^{A}	74
6	45		45	90	0.71^{AB}	98	0.75^{ABC}	104	0.24^{A}	74
7	45		90	135	0.69^{ABC}	98	0.74^{ABCD}	104	0.26^{A}	74
8	45		45	90	0.68^{BCD}	98	0.76^{Ab}	104	0.27^{A}	74
9	90		0	90	0.70^{ABC}	98	0.77^{A}	104	0.28^{A}	74
10	90		45	135	0.70^{ABC}	98	0.77^{AB}	104	0.27^{A}	74
11	90		45	135	0.71^{A}	98	0.77^{A}	104	0.26^{A}	74
12	90		90	180	0.69^{ABC}	98	0.75^{ABC}	104	0.26^{A}	74
13	45	45	45	135	0.73^{A}	98	0.76^{ABC}	104	0.26^{A}	74
14	0	45	45	90	0.68^{BCD}	98	0.72^{BCDE}	104	0.27^{A}	74
SED					0.1		0.1		0.1	
TRT					*		*		ns	

GDD= growing degree days, number of days from planting to sensing where growth was possible, GDD was determined as (Tmin+Tmax)/2 – 4.4°C.

NDVI= normalized difference vegetative index

Means followed by the same letter were not significantly different, alpha= 0.05.

*, Significant at the 0.01 probabilty level, respectively; ns= nonsignificant.

Preplant N applied as AN (34-0-0), topdress N applied as UAN (28-0-0)

SED= standard error of the difference between two equally replicated means

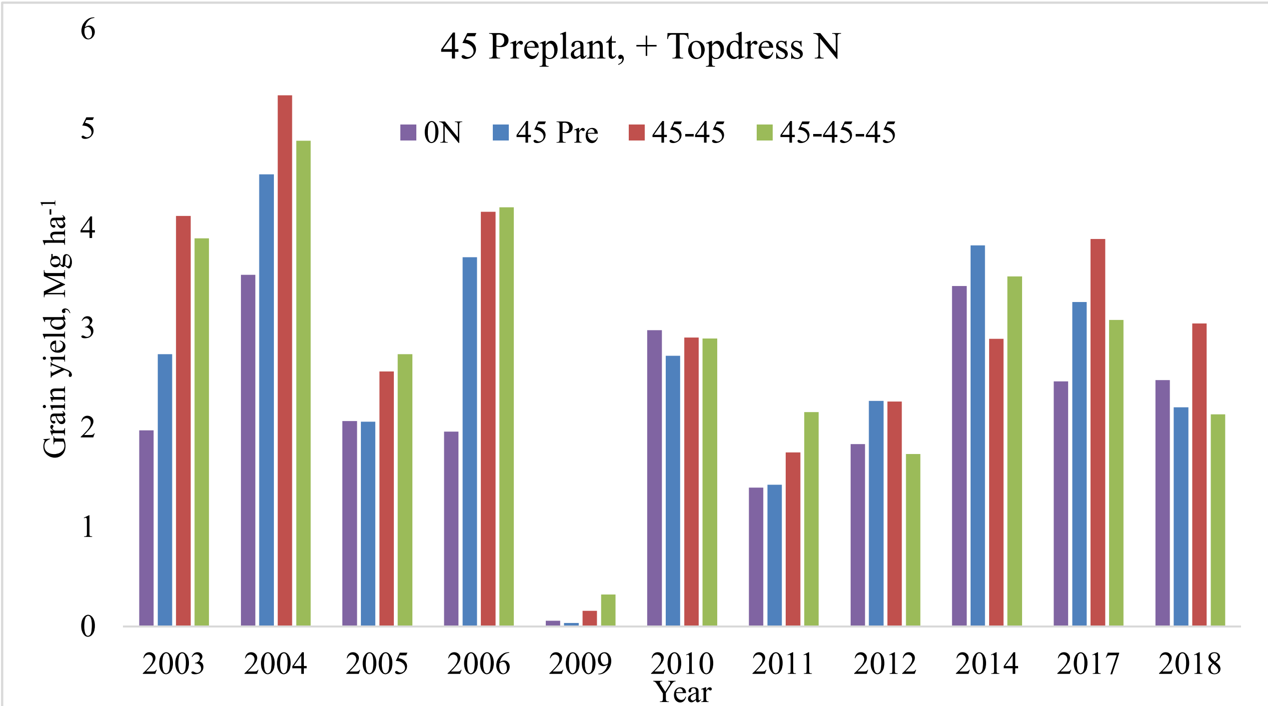

Figure 9. Comparison of preplant and topdress N application on grain yield, LCB, 2003-2018.

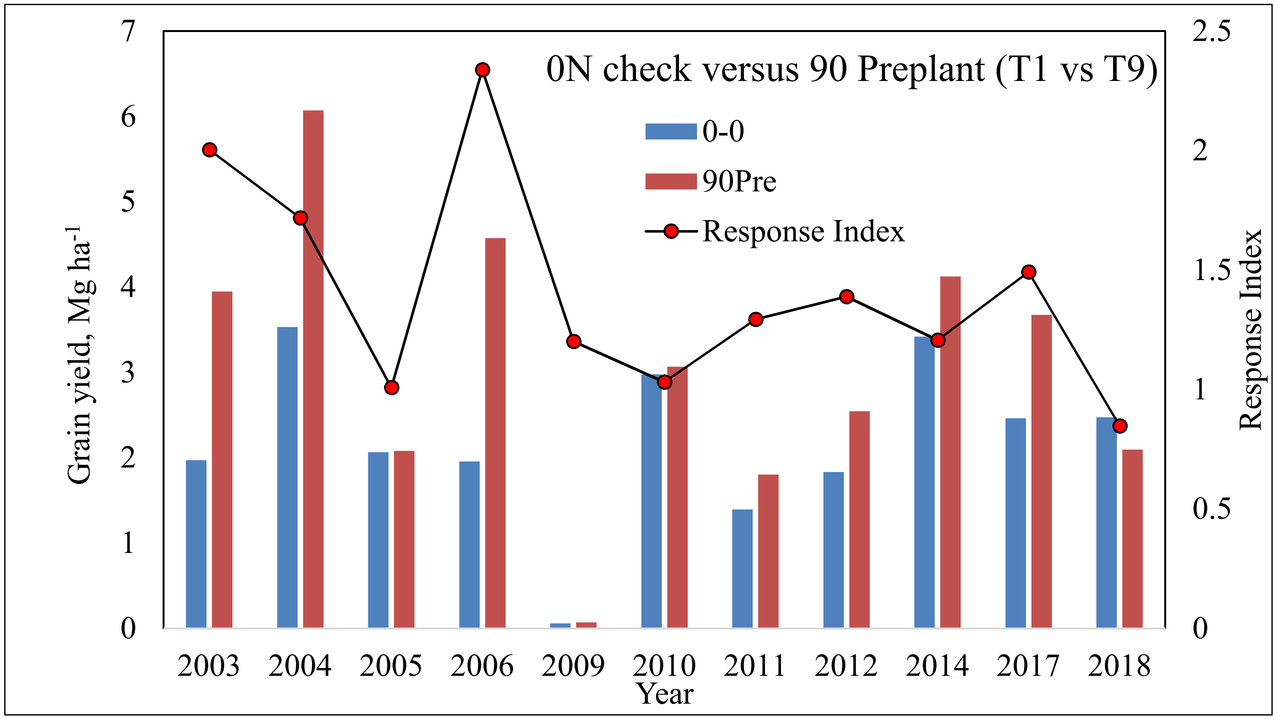

Figure 10. Comparison of check and 90 preplant N application on grain yield, LCB, 2003-2018.

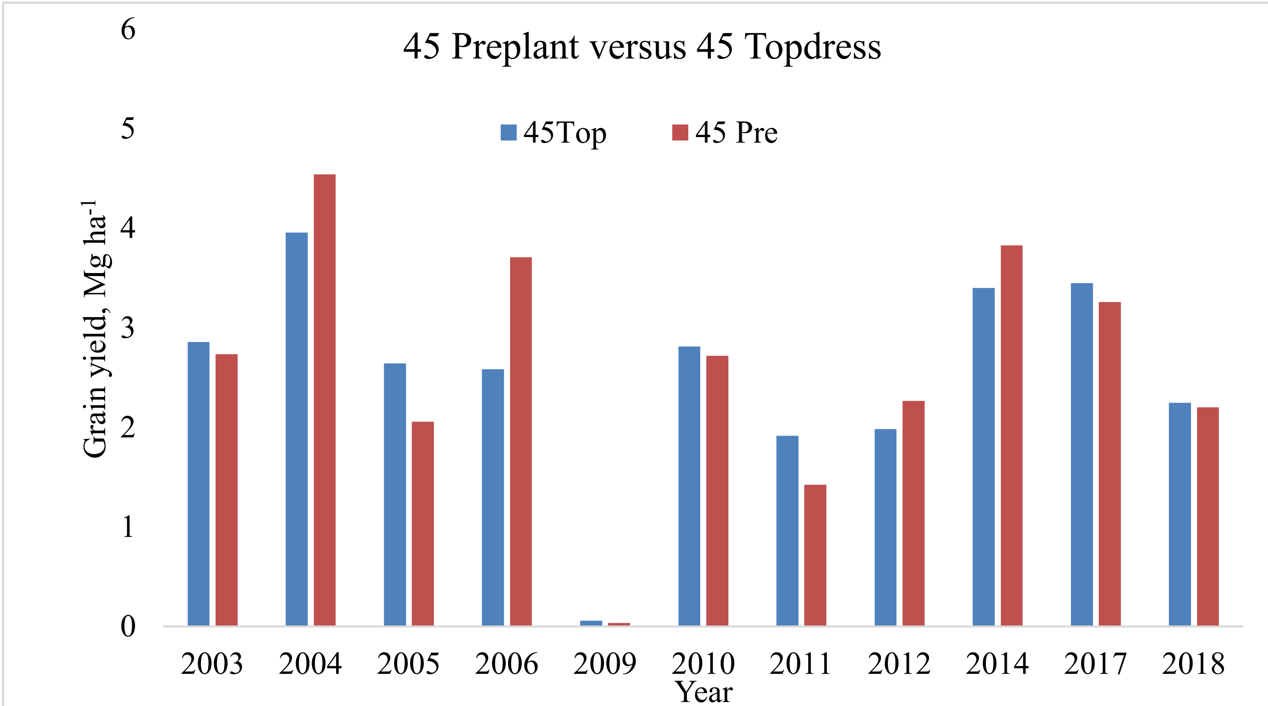

Figure 11. Comparison of 45 kg ha^{-1} preplant and 45 kg ha^{-1} topdress N on grain yield, LCB, 2003-2018.

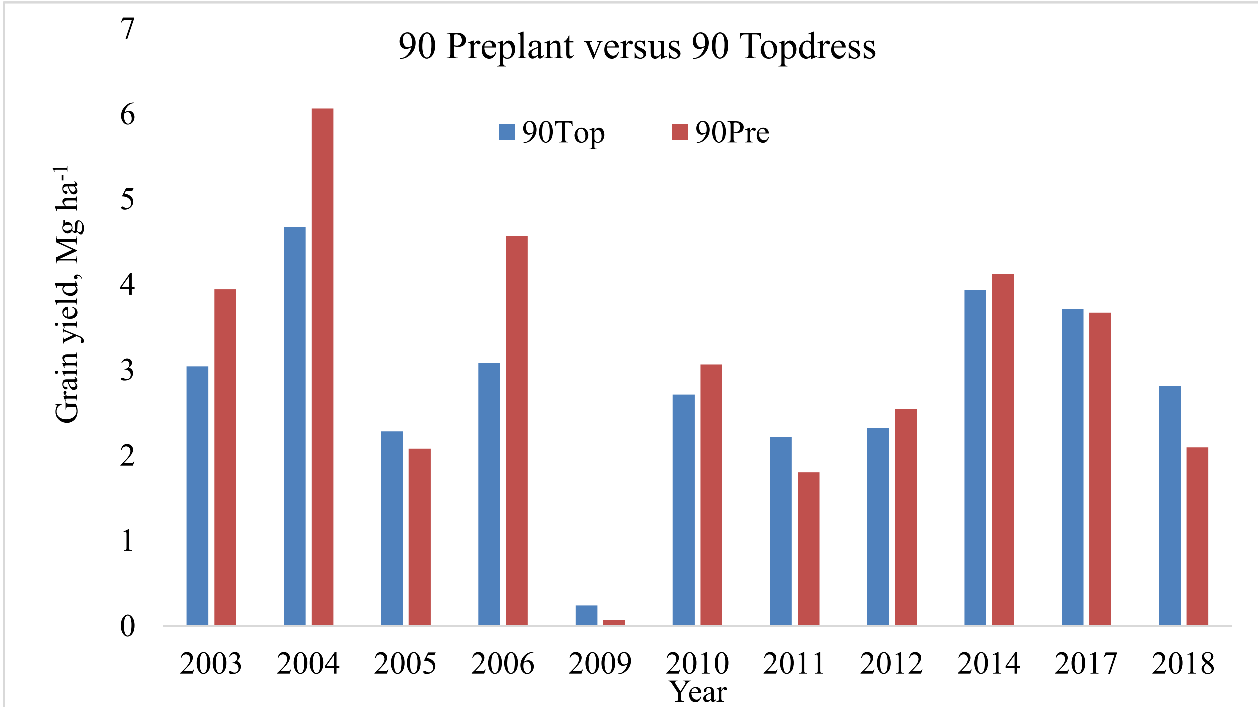

Figure 12. Comparison of 90 kg ha^{-1} preplant and 90 kg ha^{-1} topdress N on grain yield, LCB, 2003-2018

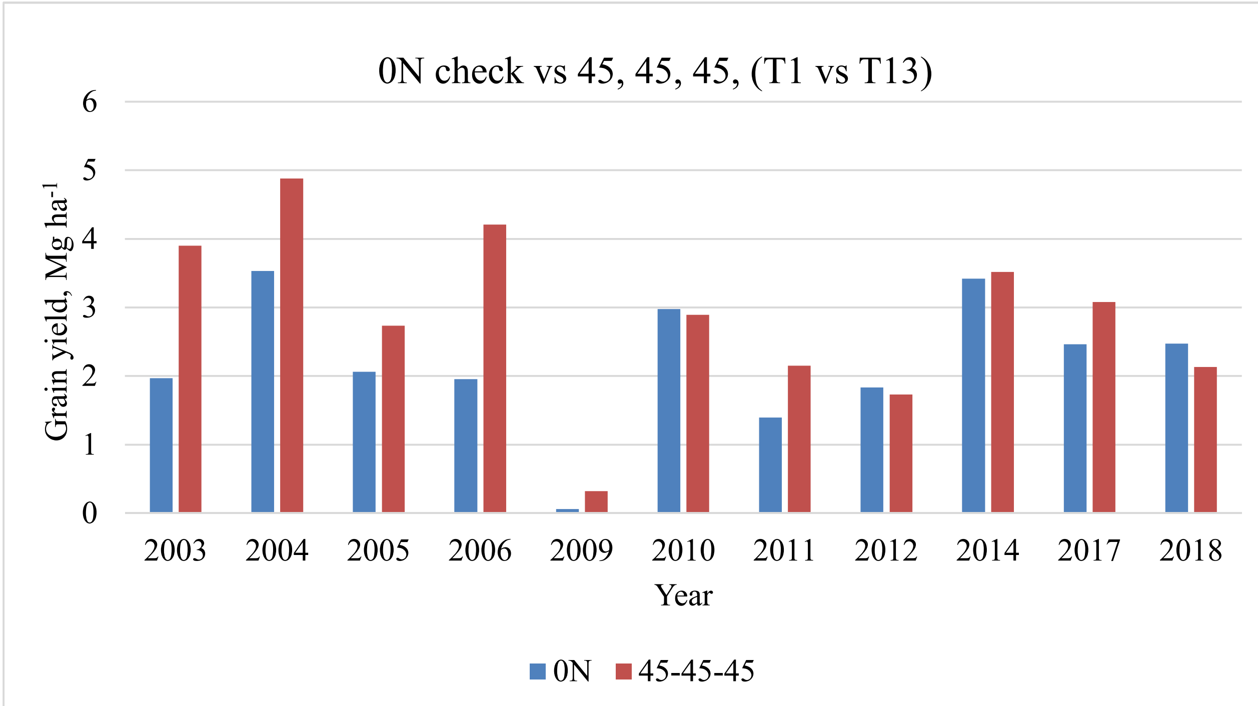

Figure 13. Comparison of zero N check and triple split N application on grain yield, LCB, 2003-2018.

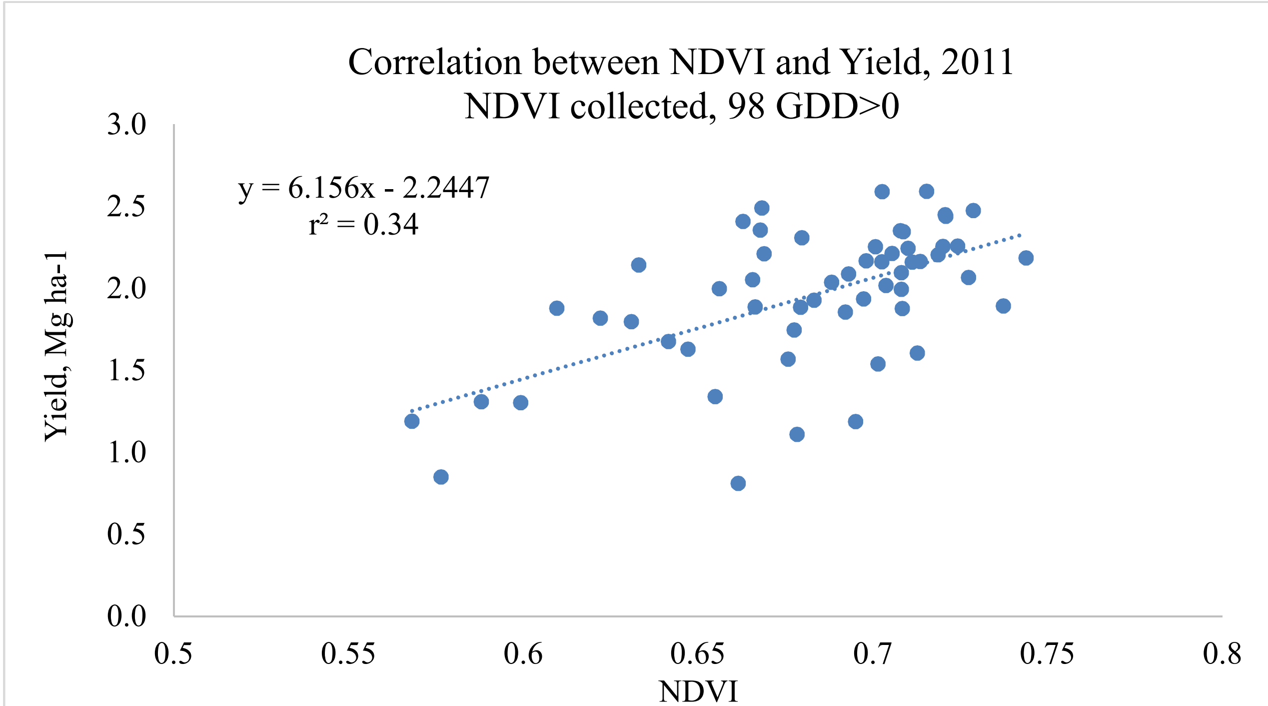

Figure 14. Correlation between NDVI and grain yield at 98 GDD, LCB, 2011.

*GDD= growing degree days, number of days from planting to sensing where growth was possible, GDD was determined as (Tmin+Tmax)/2 – 4.4°C.

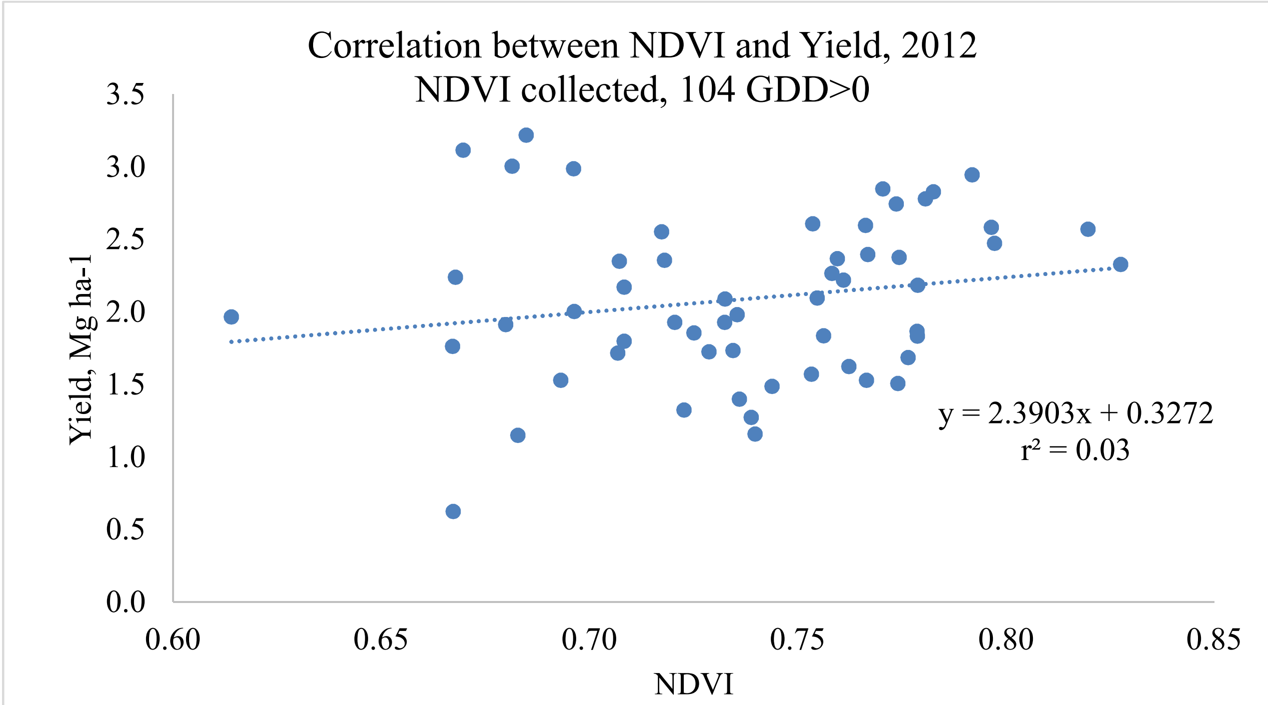

Figure 15. Correlation between NDVI and grain yield at 104 GDD, LCB, 2012.

*GDD= growing degree days, number of days from planting to sensing where growth was possible, GDD was determined as (Tmin+Tmax)/2 – 4.4°C.

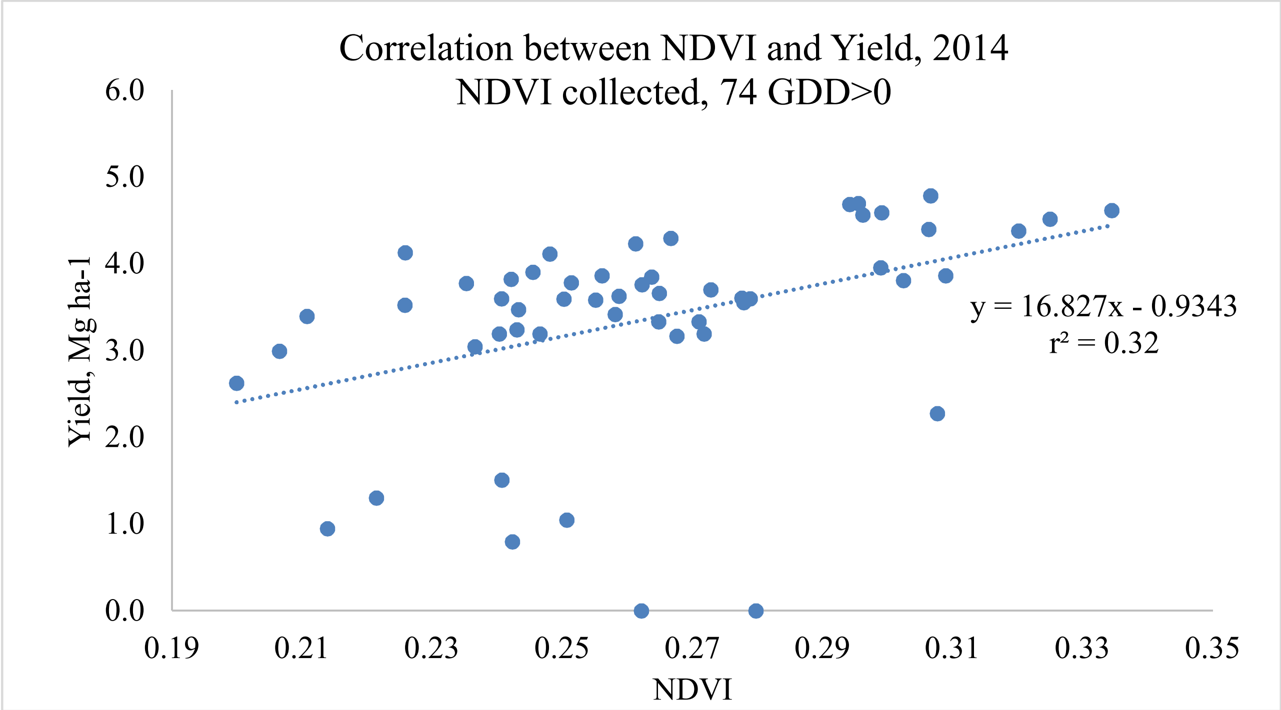

Figure 16. Correlation between NDVI and grain yield at 74 GDD, LCB, 2014.

*GDD= growing degree days, number of days from planting to sensing where growth was possible, GDD was determined as (Tmin+Tmax)/2 – 4.4°C.

REFERENCES

Chapter 1

2016 Soy Highlights. Soy Stats 2017 (2017). Available at: http://soystats.com/2013-highlights/. (Accessed: 20th March 2018).

Could Weather Affect Your Soybean Quality? (2019, August 29). Retrieved March 5, 2020, from https://www.unitedsoybean.org/article/could-weather-affect-your-soybean-quality.

Davidson, D. Soybeans Require Sulfur. IL Soy Advisor (2014). Available at: http://www.ilsoyadvisor.com/agronomy/2014/november/soybeans-require-sulfur/. (Accessed: 23rd March 2018).

De Kok, L.J., Castro, A., Durenkamp, M., Koralewska, A., Posthumus, F.S., Stuiver, C.E.E., Yang, L. and Stulen, I., 2005. Pathways of plant sulfur uptake and metabolism-an overview. Landbauforschung Völkenrode, Special Issue, 283, pp.5-13. Farhad, I. S. M., Islam, M. N., Hoque, S. & Bhuiyan, M. S. I. Academic Journal of Plant Sciences. Role of Potassium and Sulphur on the Growth, Yield and Oil Content of Soybean (Glycine max L.) 99–103 (2010).

Fenn, M.E., A. Bytnerowicz, S. L. Schilling, and C.S. Ross`. 2015. Atmospheric deposition of nitrogen, sulfur and base cations in jack pine stands in the Athabasca Oil Sands Region, Alberta, Canada. Environmental Pollution, 196, pp.497-510

Haun, W. Optimizing Soybean Production with Sulfur. Biodiesel Success | Illinois Soybean Association (2018). Available at: https://www.ilsoy.org/on-farm/ilsoyadvisor/optimizing-soybean-production-sulfur. (Accessed: 19th November 2018).

Hest, D. High Oil Pays Premiums. Farm Industry News (2001). Available at: http://www.farmindustrynews.com/high-oil-pays-premium. (Accessed: 23rd March 2018).

Industry Voice by The Mosaic Company. The importance of elemental and sulfate sulfur for your crops. Corn and Soybean Digest (2018). Available at: http://www.cornandsoybeandigest.com/soil-health/importance-elemental-and-sulfate-sulfur-your-crops. (Accessed: 23rd March 2018).

International: World Soybean Production. (2017). Available at: http://soystats.com/soybean-oil-u-s-production-history/. (Accessed: 20th March 2018).

International: World Soybean Export. (2017). Available at: http://soystats.com/international-world-soybean-exports/. (Accessed: 20th March 2018).

International: World Soybean Meal Exports (2017). Available at: http://soystats.com/international-world-soybean-meal-exports/. (Accessed: 20th March 2018) Kumar Mahesh, B.K. Nad and P. Raina (2009). Effect of phosphorus and sulphur applied along with FYM and green leaf manure on their uptake and yield of mustard and soybean. J. AridLegumes., 6 (2): 96-100.

Lee, S., Van, K., Sung, M., Nelson, R., LaMantia, J., McHale, L.K. and Mian, M.R., 2019. Genome-wide association study of seed protein, oil and amino acid contents in soybean from maturity groups I to IV. Theoretical and Applied Genetics, 132(6), pp.1639-1659.

Majumdar, B., M.S. Venkatesh, B. Lal and Kailash Kumar (2001). Response of soybean (Glycine max) to phosphorus and sulphur in acid alfisol of Meghalaya. Indian Journal of Agronomy, 46 (3): 500-505.

Messina, M., Messina, V., and Setchell, K.D.R. 1994. The Simple Soybean and Your Health. Avery Publishing Group, Garden City Park, New York.

Ramesh, N., 2002. Contract design in soybean production.

Schnug, E., Ji, L. & Zhou, J. Landbauforschung Völkenrode. Aspects of sulfur nutrition of plants; evaluation of China's current, future and available resources to correct plant nutrient sulfur deficiencies - report of the first Sino-German Sulfur Workshop 1–4 (2005).

Schoenau, J.J. and Malhi, S.S., 2008. Sulfur forms and cycling processes in soil and their relationship to sulfur fertility. Sulfur: A missing link between soils, crops, and nutrition, (sulfuramissingl), pp.1-10.

Soy Grown in the USA. Soy Connection by the United Soybean Board (2017). Available at: http://www.soyconnection.com/GrownInTheUSA. (Accessed: 20th March 2018).

Stiers, J. Oklahoma Soy Producers Have a Global Reach, Local Touch. Farm Flavor (2016). Available at: https://www.farmflavor.com/oklahoma/missouri-soy-producers-global-reach-local-touch/. (Accessed: 23rd March 2018).

Terman, G.L., Ramig, R.E., Dreier, A.F. and Olson, R.A., 1969. Yield□Protein Relationships in Wheat Grain, as Affected by Nitrogen and Water 1. Agronomy Journal, 61(5), pp.755-759.

Tisdale, S. L., Nelson, W. L. & Beaton, J. D. Soil Fertility and Fertilizers. (MacMillan Publishing Company, 1975).

U.S. Planting Data: Crop Area Planted. Soy Stats 2017 (2017). Available at: http://soystats.com/planting-data-crop-area-planted/. (Accessed: 20th March 2018).

U.S. Planting Data: Soybean Area Planted by State (2017). Available at: http://soystats.com/planting-data-soybean-area-planted-by-state/. (Accessed: 20th March 2018)U.S. Value: Crop Value by State (2017). Available at: http://soystats.com/crop-value-state/. (Accessed: 20th March 2018).

U.S. Yield & Production: Production History (2017). Available at: http://soystats.com/u-s-yield-production-production-history/. ((Accessed: 20th March 2018).

White, T. (2017, January 12). United States Department of Agriculture. Retrieved March 6, 2020, from https://www.nass.usda.gov/Newsroom/archive/2017/01_12_2017.php

Wykes, B. Looking Beyond Soybean Yields Meeting Customer Needs With High Protein and Oil. Illinois Soybean Association Available at: https://www.ilsoy.org/sites/default/files/documents/1746.pdf. (Accessed: 23rd March 2018).

Zhang, H., Raun, B., & Arnall, B. (2017, October 17). OSU Soil Test Interpretations - Oklahoma State University. Retrieved March 5, 2020, from http://factsheets.okstate.edu/documents/pss-2225-osu-soil-test-interpretations/

Chapter 2

Alcoz, M. M., Hons, F. M. & Haby, V. A. Nitrogen Fertilization Timing Effect on Wheat Production, Nitrogen Uptake Efficiency, and Residual Soil Nitrogen. Agronomy Journal 85, 1198 (1993).

Bacon, P.E., Hoult, E.H. and McGarity, J.W., 1986. Ammonia volatilization from fertilizers applied to irrigated wheat soils. Fertilizer Research, 10(1), pp.27-42. Baloch D.M. Khan M.A., Kakar E. and Malghani M.A.K. 2010. A Model for Making Field-Based Nitrogen Recommendations for Winter Wheat in Western Oregon. Journal of the Chemical Society of Pakistan. Volume: 32 Issue: 2 Pages: 147-155.

Bauer, S.J., Horgan, B.P., Soldat, D.J., Lloyd, D.T. and Gardner, D.S., 2017. Effects of low temperatures on nitrogen uptake, partitioning, and use in creeping bentgrass putting greens. Crop Science, 57(2), pp.1001-1009.

Bond, J. & Liefert , O. Wheat Outlook. United Nations Department of Agriculture (2017). Available at: https://www.ers.usda.gov/webdocs/publications/83505/whs-17e.pdf?v=42867. (Accessed: 16th May 2018).

Boman R.K., R.L. Westerman, W.R. Raun and M.E. Jojola. 1995. Time of nitrogen application: Effects on winter wheat and residual soil nitrate. Soil Sci. Soc. Am. J. 59:1364–1369.

Cooper, J.E. 1974. Effects of post-planting applications of nitrogenous fertilizers on grain yield, grain protein content, and mottling of wheat. Queensl. J. Agric. Anim. Sci. 31:33–42.

Dellinger, A.E., Schmidt, J.P. and Beegle, D.B., 2008. Developing nitrogen fertilizer recommendations for corn using an active sensor. Agronomy Journal, 100(6), pp.1546-1552.

Dhillon J, B. Figueiredo,E. Eickhoff, and W. Raun.2020a. Applied use of growing degree days to refine optimum times for nitrogen stress sensing in winter wheat (Triticum aestivum L.). Agronomy Journal.1–13. https://doi.org/10.1002/agj2.20007.

Dhillon, J., E. Eickhoff, L. Aula, P. Omara, G. Weymeyer, E. Nambi, F. Oyebiyi, T. Carpenter, W. Raun. 2020b. Nitrogen management impact on winter wheat (Triticum aestivum L.) grain yield and estimated plant nitrogen loss. Agronomy Journal, 1– 14. Retrieved from https://doi.org/10.1002/agj2.20107.

Davies, D.B., L.V., Vaidynathan, J.S. Rule, and R.H. Jarvis. 1979. Effect of sowing date and timing and level of nitrogen application to direct drilled winter wheat. Exp. Husb. 35:122-131.

Ellen J., and J.H.J. Spiertz. 1980. Effects of rate and timing nitrogen dressing on grain yield formation of winter wheat. Fert. Res. 1(3):177-190.

Fowler D.B. and J. Brydon. 1989. No-till winter wheat production on the Canadian Prairies: Timing of nitrogen fertilization. Agron J. 81:817–825.

Hubbard, R.H., L.E. Asmussen, and H.D. Allison. 1984. Shallow groundwater quality beneath an intensive multiple cropping system using center pivot irrigation. J. Environ. Qual. 13:156-161.

Hunter A.S. and G. Stanford. 1973. Protein content of winter wheat in relation to rate and time of nitrogen fertilizer application. Agron. J. 65:772–774.

Kanampiu, F.K., Raun, W.R. and Johnson, G.V., 1997. Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. Journal of Plant Nutrition, 20(2-3), pp.389-404.

Kelley, K.W. 1995. Rate and time of nitrogen applications for wheat following different crops. J. Prod. Agric. 8:339–345.

Keeney, D.R. and Follett, R.F., 1991. Managing Nitrogen for Groundwater Quality and Farm Profitability: Overview and Introduction1. Managing nitrogen for groundwater quality and farm profitability, (managing nitrogen), pp.1-7.

Keeney, D. and Olson, R.A., 1986. Sources of nitrate to ground water. Critical Reviews in Environmental Science and Technology, 16(3), pp.257-304.

Lutcher L.K. and R.L. Mahler. 1988. Sources and timing of spring topdress nitrogen on winter wheat in Idaho. Agron. J. 80:648–654.

Mahler, R. L., Koehler, F. E. & Lutcher, L. K. Nitrogen Source, Timing of Application, and Placement: Effects on Winter Wheat Production. Agronomy Journal 86, 637 (1994).

Mascagni H.J. Jr. and W.E. Sabbe. 1991. Late spring nitrogen applications on wheat on a poorly drained soil. J. Plant Nutr. 14: 1091–1103.

Mohammed, Y.A., Kelly, J., Chim, B.K., Rutto, E., Waldschmidt, K., Mullock, J., Torres, G., Desta, K.G. and Raun, W., 2013. Nitrogen fertilizer management for improved grain quality and yield in winter wheat in Oklahoma. Journal of plant nutrition, 36(5), pp.749-761.

Mulvaney R. L., S. A. Khan and T. R. Ellsworth. 2006. Need for a Soil-Based Approach in Managing Nitrogen Fertilizers for Profitable Corn Production. Soil Sci. Soc. Am. J. 70:172-182.

Omara, Peter, L. Aula, J. S. Dhillon, F. Oyebiyi, E. Eickhoff, E. Nambi, A. Fornah, J. Carpenter, and W. Raun. 2020. Variability in Winter Wheat (Triticum aestivum L.) Grain. Yield Response to Nitrogen Fertilization in Long-Term Experiments. Communications in Soil Science and Plant Analysis: 1-10.

Pushman, F.M., and J. Bingham. 1976. The effects of a granular nitrogen fertilizer and a foliar spray of urea on the yield and bread making quality of ten winter wheats. J. Agric. Sci. (Cambridge) 87:281–292.

Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357-363.

Raun W. R., J. B. Solie, R. K. Taylor, D. B. Arnall, C. J. Mack and D. E. Edmonds. 2008. Ramp Calibration Strip Technology for Determining Midseason. Agron. J. 100:1088–1093 (2008).

Ritter, W.F. and Chirnside, A.E.M., 1987. Influence of agricultural practices on nitrates in the water table aquifer. Biological wastes, 19(3), pp.165-178.

Roth, G.W., and H.G. Marshall. 1987. Effects of timing nitrogen fertilization and a fungicide on soft winter wheat. Agron. J. 79:197-200.

Tilman D. 1999. Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proc. National Academy of Sciences of the United States of America. 96(11):5995-6000.

Wise, K., Johnson, B., Mansfield, C., & Krupke, C. (2011, March). Managing Wheat by Growth Stage. Retrieved March 13, 2020, from https://www.extension.purdue.edu/extmedia/ID/ID-422.pdf

Welch L.F., P.E. Johnson, J.W. Pendleton and L.B. Miller. 1966. Efficiency of fall- vs. spring-applied nitrogen for winter wheat. Agron. J. 58:271–274.

Westcott, M. 1998. How to get higher spring wheat protein more efficiently. MT9806ag. Montana State Univ. Ext. Serv., Bozeman.

Whitmore, A.P., and T.M. Addiscott. 1986. Computer simulation of winter leaching losses of nitrate from soils cropped with winter wheat. Soil Use Manage. 2(1):26-30.

Woolfolk, C.W., William R. Raun, Gordon V. Johnson, Wade E. Thomason, Robert W. Mullen, Kathie J. Wynn and Kyle W. Freeman. 2002. Influence of Late-Season Foliar Nitrogen Applications on Yield and Grain Nitrogen in Winter Wheat. Agron. J. 94:429-434.

World population projected to reach 9.7 billion by 2050 | UN DESA Department of Economic and Social Affairs. United Nations Available at: http://www.un.org/en/development/desa/news/population/2015-report.html. (Accessed: 16th May 2018)

Wuest S.B. and K.G. Cassman. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: I. Uptake efficiency of preplant vs. late season application. Agron. J. 84:682–688.

VITA

Gwendolyn Bess Wehmeyer

Candidate for the Degree of

Doctor of Philosophy

Dissertation: I. OPTIMUM SULFUR APPLICATION FOR SOYBEAN (Glycine max) IN OKLAHOMA

II. INFLUENCE OF PREPLANT TOPDRESS ON WINTER WHEAT (Triticum Aestivum) GRAIN YIELDS

Major Field: Soil Science

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Soil Science at Oklahoma State University, Stillwater, Oklahoma in May, 2020.

Completed the requirements for the Master of Science in Plant and Soil Sciences at Oklahoma State University, Stillwater, Oklahoma in 2017.

Completed the requirements for the Bachelor of Science in Agriculture Business at Northwest Missouri State University, Maryville, Missouri in 2015.

Experience:

Research Associate, Oklahoma State University, 2016-2019
Intern, Five Star COOP, 2014
Intern, Sydensticker Implement Company, Moscow Mills, MO, 2013

Professional Memberships:

American Society of Agronomy, 2017
Crop Science Society of America, 2017
Soil Science Society of America, 2017