INVESTIGATING AVENUES OF INCREASING NUTRIENT USE EFFICIENCY IN SOYBEANS AND WINTER WHEAT IN OKLAHOMA

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Abstract:

A large part of the land-grant mission is to increase production and sustainability in growing crops to feed and clothe our world. One aspect that allows us to get closer to obtaining our goal is to increase our nutrient use efficiency (NUE). Increasing our NUE allows producers to reduce waste and increase profits. This has led to the development of a strategy to increase NUE, known as the 4R's of Nutrient Stewardship Concept (Johnston & Bruulsema, 2014). The 4R's stand for applying the right source of nutrients, at the right rate, at the right time, in the right place. Many research studies in the past two decades have utilized that concept to influence nutrient recommendations. This dissertation aims to assess Oklahoma State University's (OSU) nutrient recommendations for optimizing yield, as well as utilizing two of the 4R's (right rate, right time) to refine nutrient recommendations. We conclude that while on average, OSU's nutrient recommendations perform well optimizing yields, there are avenues for refinement to increase NUE in soybeans and winter wheat in Oklahoma.

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CHAPTER I

INTRODUCTION

Producers aim to maximize production while still staying profitable with inputs. Over the past 15 years, the average price of soybeans and winter wheat have been variable, while for the most part, the cost of fertilizer has steadily increased (USDA-NASS, 2020). This challenges researchers with providing the information that allows producers to maximize their profits, while optimizing inputs. One option is aiding producers against production cost by increasing nutrient use efficiency (NUE).

Nutrient use efficiency is the efficiency of a crop to utilize nutrients that are both from the soil and fertilizer application to produce grain (Raun & Johnson, 1999). Estimation of the world's nutrient use efficiency has shown to be 33, 16, and 19% for N, P, and K, respectively (Dhillon et al., 2019). Though these are estimates, such low use efficiencies are not sustainable at today's standards. Increasing these values has become a mission within the agronomic community, leading to the formation of the 4R nutrient stewardship concept (Johnston & Bruulsema, 2014). The 4R's stand for applying the right source of nutrients, at the right rate, at the right time, and in the right place. Using these guidelines, the following chapters will aim at increasing the knowledge of nutrient use efficiency-nitrogen (NUE_N) (Mallarino et al., 2001) in winter wheat (*Triticum aestiveum*), and nutrient use efficiency-potassium (NUE_K) in soybean (*Glycine max*).

CHAPTER II

REVIEW OF LITERATURE

Fundamental concepts of soil fertility

Utilizing soil testing in agronomic practices was increased exponentially by the work of Bray (1954) by identifying two different types of zones of nutrient uptake for plants. The largest zone occupies area surrounding the root system and is deemed the sorption zone. Nutrients that are mobile within the soil can be absorbed within this sorption zone. The root zone is the smaller zone which occupies the area directly adjacent to the root surface. By the mobility concept, Bray postulated that mobile nutrient requirements could be based on earlier work by von Liebig's "law of the minimum", where nutrient requirement could be based upon the yield of the crop; immobile nutrient requirements could be based on sufficiency concept. These fundamental concepts of soil fertility led to further work understanding requirements of mobile and immobile nutrients within plant growth.

4R's of Nutrient Stewardship

Over-application of nutrients has been a concern in the past 2 decades, due to issues with increasing levels of nutrients in drinking water, and eutrophication in large bodies of water. There has been a push from environmentalists, regulators, and producers alike to decrease waste, increase efficiencies, and decrease costs by increasing agriculture industry's nutrient use efficiency (NUE). The 4R's of nutrient stewardship were developed in the late 2000's as a global strategy to increase NUE through best management practices (Johnston & Bruulsema, 2014). The 4R's represent Right Source, Right Rate, Right Time, and Right Placement.

Nitrogen Timing

One aspect of increasing nutrient use efficiency is by applying fertilizer at the right time, one of the 4R's of nutrient stewardship (Mallarino et al., 2001). Melaj et al. (2003), evaluating N fertilizer timing in winter wheat (*Triticum aestiveum)* in Argentina, found that lowest values of NUE_N were found in pre-plant fertilizer applications, and applications at or near the Feekes 3 growth stage. The authors hypothesized this was due to greater opportunity for N loss, via immobilization, leaching, etc., while the plant is not using N due to vernalization. The highest amount of N uptake was found to be around the time of rapid wheat growth, in the spring during green-up, approximately Feekes 4.

Souza (2018) echoed these results, reporting that delaying N fertilizer in hard red winter wheat in Oklahoma did not lead to a loss in grain yield as late as Feekes 9, even when the crop showed N deficiencies prior to Feekes 5. A significant finding of this study was that the highest usage efficiency of fertilizer applied was found to be when the crop was growing at higher rates, around Feekes 7.

Nitrogen Rate and SBNRC

Another R of the 4R's of nutrient stewardship is apply nutrients at the right rate. Applying the correct rate of N fertilizer can greatly affect the NUE_N of that crop. While over-applying fertilizer could lead to maximizing yield, the crop cannot utilize all of applied N therefore decreasing the NUE_N and likelihood of environmental contamination (leaching), or waste due to luxury N. The under application of N can lead to the crop using most of the available N, having a high NUE, however, not maximizing its potential grain yield.

Nitrogen is required in largest amounts for plants, and yet, is one of the least present nutrients found in the soil, due to other factors such as leaching, volatilization, and microorganisms (Brady, 1984). In the late 20th century, soil testing was notably the most widely used tool used to estimate nutrient requirements. Oklahoma State University recommendations utilized early work to develop a recommendation of 0.03 kg N ha^{-1} per 1kg ha^{-1} increase in yield, subtracting the amount of N in the soil derived from the soil test. The soil sampling strategy generally used was composite sampling over a field; taking multiple subsamples from throughout the field to come up with a composite sample over a large area. With soil testing being a singular instance look at the soil nutrient availability; it is harder to understand how it fluctuates over an area. Kincheloe (1994) noted that yield variations occur in fields that have continually received similar inputs, as variability across the field could be quite large. Utilizing grid sampling techniques (dividing fields into grids for systematic sampling) can offer opportunities for understanding spatial variability of a field, but can become both time and financially costly. Another method was sought after to aid in nutrient recommendations.

In the late 1990's and early 2000's, research was conducted that aimed to aid in-season nutrient requirements. Filella et al. (1995) recorded that remote sensing could provide inexpensive monitoring of N deficiency and be used to monitor N status, as a function of chlorophyll concentration. Raun et al. (2001) noted that using remote sensing values could provide an in-season estimate of yield (INSEY). These optical sensor readings taken from an active sensor gives a value of reflectance, read as normalized difference vegetation index (NDVI), which is then used to calculate a N rate. The formula can be found below.

$$\boldsymbol{INSEY = \frac{NDVI}{GDD > 0}} \tag{1}$$

The INSEY was evaluated using the NDVI from an in-season sensor reading, and growing degree days greater than 0 (GDD>0), or the amount of days from planting where average ambient temperature is above a temperature threshold for which there is growth; for wheat, this temperature is 4.4° C. These variables were chosen to calculate INSEY to reflect the growth of the biomass of the crop over the growing season, which was found to have a high coefficient of determination (r^2) with grain yield. Dividing the NDVI by GDD>0 allows for an estimation of NDVI value increase per growing day, or a growth factor.

Calculation of INSEY was used to develop the first N fertilization optimization algorithm. This is because once the estimate of predicted yield potential is provided, the amount of N uptake for that growing crop can be calculated. The first algorithm is as follows.

$$\boldsymbol{YP_0 = 0.74076 + 0.10210 \times e^{577.66 * INSEY}} \tag{2}$$

Where YP_0 is the predicted grain yield in Mg ha^{-1}. INSEY is calculated using the equation listed former.

$$\boldsymbol{RI_{NDVI} = \frac{NDVI_{0N}}{NDVI_{N\ Rich}}} \tag{3}$$

RI_{NDVI} is the response index calculated by dividing the NDVI values of the check, or 0 N, plot, by the NDVI values of the N-rich strip. Using the RI_{NDVI}, an estimate of yield with an N application can be calculated by multiplying by the estimate of the check, or 0 N, plot, as seen below.

$$\boldsymbol{YP_N = YP_0 \times RI_{NDVI}} \tag{4}$$

$$\boldsymbol{PNG = 0.0703 \times (YP_0)^2 - 0.5298 \times YP_0 + 3.106} \tag{5}$$

Where PNG is the total grain N. This formula was developed based on samples taken from 1980 to 1999 to estimate N grain content based on INSEY (Raun et al., 2001).

$$GNUP = YP_N \times PNG \quad (6)$$

GNUP is the predicted N uptake for the grain, calculated by multiplying the estimated yield with N application (YP_N)

$$FNUP = 14.76 + 0.7758 \times e^{5.468 \times NDVI} \quad (7)$$

FNUP is the early-season forage N uptake based on NDVI.

$$FNR = \frac{GNUP - FNUP}{NUE_N} \quad (8)$$

FNR is the in-season top-dress N fertilizer requirement based upon the difference of the uptake of N already taken up by the plant (FNUP), and the estimation of uptake of the grain (GNUP), divided by the expected NUE, or nitrogen use efficiency, of the fertilizer applied. In this equation, 0.70 was used as NUE_N to quantify that approximately 70% of the applied N would be utilized by the growing crop. This procedure, when applied in across the scale of a field, can lend to an increase of application of N in high yield potential zones within a field, while decreasing N fertilizer in areas of low yield potential. Simplified, the current N Rate portion of the Oklahoma State University (OSU) SBNRC algorithm is as follows.

$$Rate_N = \frac{(YP_N - YP_0) \times PNG}{NUE} \quad \textbf{(9)}$$

Over time, the algorithm was modified in order to better fit the collection of data being amassed. The current algorithm currently utilized and recommended by OSU is as follows:

$$\boldsymbol{YP_0 = 1711 \times e^{INSEY*137.2}} \tag{10}$$

In-season sensing allowed for an estimate of the crops yield potential based upon current growing conditions, however, did not take into account any post-sensing stresses. The exponential curve created by the algorithm took into account all data points from trials, many of which could have endured these post-sensing stresses that decreased the yield potential for those locations, therefore skewing the curve. The goal of the model was to provide an estimate of yield unaffected by post-sensing conditions, not one that would over or under predict yield for each location, again due to being skewed by prior data. Therefore, it was chosen to adjust the model by one standard deviation so that only 32% of the total data points that made up the model were above the curve, or, underestimating yield (Raun et al., 2005).

Response index has the opportunity to underestimate benefits to additional N, especially in the median responsive sites (Raun et al., 2005). Response index later was adjusted in order to reflect the relationship between RI_{NDVI} and $RI_{Harvest}$, in order to better serve those sites. This adjustment allowed for locations that did respond with little amounts to have a larger impact on the N rate calculation.

$$\boldsymbol{RI_{Harvest} = 1.69 \times (RI_{NDVI}) - 0.70} \tag{11}$$

All this was derived using data from long term trials in Lahoma and Stillwater, OK across many years and varying conditions (Raun et al., 2005). The SBNRC, or Sensor Based Nitrogen Rate Calculator, uses this algorithm as the current sensor based recommendations for N in winter wheat. These current recommendations are based for the entire state of Oklahoma.

Climate and N Availability

Environment variability can play a large role in N uptake and availability. Nitrogen applied in its dry forms (urea, diammonium phosphate [DAP], monoammonium phosphate [MAP], ammonium nitrate, etc.) need moisture in order to dissolve into the soil solution and into sorption root zone. Large rainfall events can lead to run-off and leaching, which allowing the movement of N either too deep into the soil profile for root availability, or loss of nutrient altogether (Gu & Riley, 2010; Nearing et al., 2005).

Oklahoma's climate can vary greatly across the state. Annual temperature, precipitation, and growing season changes across the state can affect the phenological growth stages in winter wheat, and in turn, influence the growth and response to nutrients (Porter & Gawith, 1999). Oklahoma Climatological Survey divides the state of Oklahoma into 9 climatological zones, each consisting of counties that have average climates similar to their respective group. When looking at regionalizing the state for this study, climatological zones offer distinctions and characteristics between regions that are conducive for differing growing conditions, and are to be utilized for the scope of this project.

Potassium

Potassium (K) is involved in many different roles essential to a plants life. It never becomes part of a larger chemical structure, but works in regulation of nutrients and waters within the plant. Potassium becomes very important in the activation of enzymes within grain N concentration and starch production, in cellular transport, and in photosynthesis. While soil-K content exceeds crop demand in most soils, potassium deficiencies can be found, especially in areas of loose textured, highly weathered soils, as well as areas of extremely high rainfall. Soil-K that is found in soils, however, is not always plant-available. Potassium can be found in 3 different forms within the soil; fixed K, exchangeable K, and solution K. The majority of K (98%) within the soil is still in its fixed, or primary mineral-K form. It takes many years of weathering in order for this form to become available; feldspars and mica are examples of this form of K.

The next form of K is in the exchangeable, or secondary-mineral state. This form constitutes about 1-10% of the total soil K level. This form is found bonded to colloids within the soil. These colloids are found within the soil profile as clay, which is considered the most dominant factor affecting K availability in soil (Goli-Kalanpa et al., 2008).

The final form of K is the solution K, which is K suspended within soil solution. This is readily available form of K for plants, but only about 1-2% of soil K is actually in this form (Arnall, 2017). This form and exchangeable-K are in equilibrium; as one form is removed, the equilibrium shifts in order to replenish that pool, in order to move back into equilibrium. This demonstrates the ability of a soil to recover some of the potassium used while cropping without the use of fertilizer. This equilibrium is affected by the addition of K fertilizer as well. When a K fertilizer is added to the soil, a portion of the fertilizer will go into solution, able to be immediately used by the plant, and the rest will become "fixed" within the colloids in the soil and become slowly available (Brady, 1984). While not in an immediately available form, the fixed K can be resistant to leaching, unlike solution K.

Clay particles at the elemental level are silicate molecules. Composition of these silicate clays can lend to different structures of the clay particles within the soil, which in turn, can affect the availability of soil-K (Barton, 2002). Clay molecules' chemistry allows for the forming of sheets of clays in soil. The composition of the silicate clays can form into different structures: 1:1, 2:1, and 2:1:1 clays. The designation of the structure refers to the ratio of tetrahedral to octahedral arranged sheets of clays.

The 1:1 clays sheets are held together using van der Waals bonds between the tetrahedral and octahedral sheets, keeping both sheets tightly together. This limits the reactivity of the clay particles, therefore, soils dominated by 1:1 clays have minimal cation retaining capacity (Barton, 2002). This limits the pool size of the exchangeable K form, and in turn, limits the solution capacity as well, as both forms are tied to one another.

The 2:1 clay sheets consist of one octahedral clay sheet between two tetrahedral sheets. The structure of this clay sheet results in sites with negative charge, allowing for cations such as K^+ to be bonded (Barton, 2002). Depending on the elemental composition of each clay sheet, surface area and net negative charge can increase, creating more bonding sites for cations.

There are factors that have influences on K availability within the soil, such as soil pH. At low pH (4-5), the soil solution potassium concentration is very high, around 18 cmol kg^{-1} (Brady, 1984). As the soil pH increases, K^+ can be sorbed more easily. This can lead to the amount of soil solution potassium to decrease approximately 2 cmol kg^{-1}, as it becomes fixed to colloids within the soil.

Potassium can also affect drought resistance of plants. Low plant available K levels during periods of drought can make it much more difficult for crops to survive. During periods of dry weather, root growth, as well as the diffusion and uptake of K^+, is restricted (Wang et al., 2013). During these conditions, previously applied potassium has been reported to improve root growth, vegetative growth, growth rate, and improve water use efficiency (Andersen, 2009).Potassium deficiencies can occur in agriculture intensive areas that crops are intensively managed for many years, depleting much of the available and slowly available supply, and removal of much of crop residues. Furthermore, when producers are looking to decrease input costs, many will choose to reduce the amount of fertilizer used. However, this can lead to deficiencies. Potassium deficiencies can lead to stunted root development in young plants (Ashley et al., 2006). In mature plants, older leaves of plants begin to show chlorosis on the edges as the potassium is transported to newer growth. If the deficiency continues the chlorosis quickly develops into necrosis.

Current OSU recommendations utilize a sufficiency model for immobile nutrients, such as K. For soybeans, the sufficiency index is set at 137.5 mg kg^{-1}. While many studies have shown that under low soil test K (STK), K fertilizer application can increase yields (Casanova, 2000; Heckman & Kamprath, 1992; Jones et al., 1977), other studies have reported mixed results. Reed (2018) and Mallarino (2000) observed responses to K fertilizers on soils that had optimum or near-optimum levels of K, while other locations did not respond that had low STK values. This suggests that current soil test interpretations should be reevaluated for accuracy.

Foliar application of Potassium

In-season fertilizer applications generally occur in agronomic practices as a liquid or dry material application that aims to be soil absorbed, which can later be absorbed by the crop. However, there are some fertilizers available to producers that look to apply fertilizers directly to the crop, called 'foliar' fertilizers. Many of these products are made to be directly absorbed by the plant through the leaf, while others are made to be washed off via rainfall, to be later taken through the soil, or a combination of both modes. Due to insufficient documentation the level of effectiveness is unclear in regard to different types of foliar fertilizers.

With the rise and popularity of foliar fertilizers in the past few decades, it is important to determine that crops can uptake nutrients through the leaf surface. There is evidence for uptake of solutes and water through the stomata of crops (Eichert et al., 1998). In a review of many foliar application research articles, Fernández and Brown (2013) found that nutrients that are mobile within the plant seem to be translocated well from the surface into the crop and on to other organs within the plant. Based on this, foliar applied potassium should be able to be absorbed and utilized.

Nelson et al. (2010) looked at the response of timing of pre-plant and foliar potassium applications in a claypan soil in Missouri. Pre-plant fertilizer and foliar application both used the form K_2SO_4 as their fertilizer source. Researchers chose that source due to its low salt index, in order to minimize crop injury. Leaf samples were taken from the most recently mature trifoliate from 20 plants in each plot and removed before the V4, R1-R2, and R3-R4 application timings. Figure 2 displays the Leaf K concentration of K at days after V4 foliar application. For this source, the higher rate lead to a higher K concentration. For the trial, foliar K was found to be capable of being a supplemental source of K for increased tissue concentration, but not a replacement for pre-plant K for yield.

Jiménez et al. (1996) looked at the concentrations of different nutrients of soybean leaves throughout different stages of development. Researchers found that the highest concentrations of K in the foliage was at the vegetative stage, and lowest at R5. The hypothesis is that the K concentration falls later into maturity, as major source-sink distribution requires high amounts of K. Potassium is mobile in the plant, therefore, translocation would occur from the leaf into the pods.

Mallarino et al. (2001) evaluated the variation in response to soybeans to early season foliar fertilization of N-P-K-S and micronutrients. Application of the foliar treatments was done at V5, as this is the time that most producers have capability of applying foliar fertilizers. Conclusions from this trial responses were highly variable. The primary issue with foliar applications is cost over effectiveness. They concluded that in order to be economically viable, a foliar application would need to be done in the same pass with a sprayer that herbicide or other application would occur, therefore lowering the overall cost of the application. Haq and Mallarino (2005) investigated the impact of foliar applied K fertilizer on soybean oil and grain N concentration, to the same conclusion: Foliar K was not a substitution for pre-plant fertilizer.

The reviewed literature discusses N and K requirements for winter wheat and soybeans, respectively, as well as the nutrient pools within the soil, and management schemes for both nutrients. An important find within literature are the means in which nutrient use efficiency (NUE_N and NUE_K) for both soybeans and winter wheat is investigated, yet still do not answer all questions. Upon review of literature, it is apparent that increasing NUE could be examined closer, especially in the unique environments that Oklahoma offers. The following chapters aim to investigate avenues of increasing nutrient use efficiency for winter wheat and soybeans in Oklahoma.

CHAPTER III

EFFECT OF N RATE AND TIMING ON WINTER WHEAT GRAIN YIELD AND GRAIN N CONCENTRATION ACROSS VARYING ENVIRONMENTS

Introduction

Many trials have been implemented investigating nitrogen (N) timing and rate studies in winter wheat (Abedi et al., 2011; Alcoz et al., 1993; Melaj et al., 2003). Souza (2018) was interested in investigating the crop's ability to overcome N stress post-vernalization in Oklahoma. The author noted that by delaying N application into the early spring, that not only could yields be recuperated after N deficiency, but in many cases, could increase over a pre-plant application. As for grain N concentration levels, delaying N would almost always lead to an increase in grain N concentration over pre-plant levels. That trial was conducted on research stations managed by Oklahoma State University, where most locations are managed at very low levels of nutrients in order to increase chances for response to any nutrient trials. The research stations are also centrally located in Oklahoma, in areas that have large acres of wheat, but not the areas primarily known for growing wheat in Oklahoma. Producers across the state of Oklahoma, while curious about the findings of the previous trial, may still feel reluctant due to their environmental and climatic conditions which may be much different than the areas where trials were conducted.

The objective of this trial was to investigate the effect of N rate and application timing on winter wheat grain yield and grain N values across varying environments within the state of Oklahoma. The author's hypothesize that N rate and timing applications would perform similarly in varying environments across the state of Oklahoma

Materials and Methods

Study Area

The experimental design of this trial was randomized complete block design (RCBD) with a 2 x 4 factorial design structure; 2 timings (pre-plant and in-season fertilizer application, applied prior to Feekes 5 growth stage) by 4 rates (25%, 50%, 75%, 100% yield potential rate) applied as ammonium nitrate (AN, 34-0-0), with 4 replications. Site specific yield potential rate was determined using the yield potential of the area, considering the productivity of the location, environment parameters, and historical yield, and used the OSU recommendations of 0.03 kg N ha^{-1} per 1kg ha^{-1} wheat. Plot sizes were 1.8 m x 1.8 m, with 1.2 m alleys between repetitions. This study was implemented and managed to completion at a total of 19 locations across 4 climatological zones (found in Table 2 and Figure 17); 5 locations in the 2018-2019 growing season, and 15 locations in the 2019-2020 growing season.

Soil Analyses

Pre-plant composite soil samples were taken (0-15 cm), consisting of at least 15 cores, to document soil chemical properties (Table 1). Samples were dried at 65°C overnight and ground to pass a 2 mm sieve prior to extraction and analysis, conducted following methods set by Crouse et al. (2014). The pH was measured by using a combination electrode within a 1:1 ratio of soil to water suspension. Nitrate-N was extracted using a 1M KCl extraction solution with 2 g of soil to 20 mL of solution with 15 minutes of shaking time. Nitrate-N was then determined by automated colorimetric flow-injection analysis (Lachat Quickchem 8000, Loveland, CO). The Mehlich-3 (M3) method was used to find extractable P, K, Ca, and Mg, by extracting 2 g of soil with 20 mL of M3 solution and shaking for 5 minutes. Exchangeable S was found by mixing 10 g of soil with 25 mL of 0.008M calcium phosphate solution and shaking for 30 minutes. Concentration of P, K, Ca, Mg, and S in the extracts were determined with an inductively coupled plasma atomic emission spectrometer (ICP-AES). Organic matter (OM) content was determined using dry combustion methods.

Table 1 Soil Test analyses for each location. Values provided are pH, NO_3-N and SO_4-S (kg ha^{-1}), Soil test Phosphorus (STP), Soil Test Potassium (STK), Calcium and Magnesium (ppm), and Organic Matter (OM, %).

Year	**Location**	**pH**	**NO_3-N**	**SO_4-S**	**STP**	**STK**	**Ca**	**Mg**	**OM**
			kg ha^{-1}			*mg kg^{-1}*			*%*
2018-2019	Byron 1	6.8	57	7	22	225	853	312	1.4
	Capron	6.0	-	-	10	236	1430	633	1.1
	Chickasha 1	5.9	50	52	33	143	1536	511	-
	Lahoma 1	7.1	9	2	7	143	1300	542	-
	Perkins	7.4	3	2	26	142	788	184	-
2019-2020	Ballagh	7.2	9	25	23	135	2860	324	3.1
	Byron 2	5.5	68	9	17	197	696	320	1.3
	Byron 3	5.6	66	9	20	230	853	264	1.5
	Carmen	6.5	38	25	6	295	1469	503	-
	Chickasha 2	6.9	2	8	7	235	2394	963	2.1
	Dove	6.3	7	10	31	131	974	399	1.1
	El Reno	5.7	5	16	63	174	1610	429	2.0
	Elmwood	7.6	54	11	66	567	3890	265	2.3
	Granite	5.3	21	13	-	256	1446	269	1.3
	Hobart	7.8	13	4	6	390	4007	463	2.1
	Lahoma 2	6.1	9	13	7	207	3155	1202	1.4
	LCB	5.7	11	36	20	607	2545	1002	2.1
	Nardin	5.6	128	17	7	188	1749	433	2.4
	Tipton	7.2	9	7	22	225	853	312	1.4

Table 2 This table lists the growing season, the site name, climatological zone, wheat cultivar, planting date, top-dress application, and days where growing degree days were greater than zero at the top dress application. (GDD>0). Climatological zone was adapted from Oklahoma Climatological Survey. NC- North Central, C- Central, P- Panhandle, SW- South West. Planting date and Cultivar was directly reported from the producer. Top-Dress application is the date that the delayed nitrogen was applied for those treatments. GDD>0 at application is the measure of how many days had average temperatures [(Max Temp-Min Temp)/2] above 4.4° C, the temperature that is reported required for wheat growth. Recommended GDD>0 ranges for top-dress applications using optical sensors is 80-110 GDD>0.

Year	**Site**	**Zone**	**Cultivar**	**Planting Date**	**Top-Dress Application**	**GDD>0 at application**
2018-2019	Byron 1	NC	DoubleStop CL+[1]	10/20/2018	03/22/2019	79
	Capron	NC	-	10/20/2018	03/25/2019	77
	Chickasha 1	C	Smith's Gold[1]	11/06/2018	04/01/2019	92
	Lahoma 1	NC	Bentley[1]	10/18/2018	04/05/2019	97
	Perkins	C	DoubleStop CL+[1]	10/18/2018	04/03/2019	106
2019-2020	Ballagh	NC	SY Monument[2]	10/18/2019	03/28/2020	99
	Byron 2	NC	DoubleStop CL+[1]	10/01/2019	03/29/2020	121
	Byron 3	NC	DoubleStop CL+[1]	10/15/2019	03/29/2020	107
	Carmen	NC	Gallagher[1]	10/12/2019	03/29/2020	110
	Chickasha 2	C	Smith's Gold[1]	10/01/2019	02/27/2020	109
	Dove	C	Smith's Gold[1]	10/17/2019	03/27/2020	107
	El Reno	C	Smith's Gold[1]	10/02/2019	03/02/2020	99
	Elmwood	P	-	10/14/2019	03/12/2020	89
	Granite	SW	Gore[3]	10/08/2019	03/02/2020	101
	Hobart	SW	Gore[3]	10/22/2019	03/02/2020	91
	Lahoma 2	NC	DoubleStop CL+[1]	10/15/2019	03/29/2020	106
	LCB	C	Smith's Gold[1]	10/17/2019	03/27/2020	107
	Nardin	NC	Chrome[4]	11/18/2019	03/29/2020	81
	Tipton	SW	Smith's Gold[1]	11/04/2019	03/02/2020	90

1 – *Oklahoma Genetics Inc.*
2 – *Syngenta Seeds, Inc.*
3 – *UGA Ag. Experiment Station*
4 – *Limagrain Cereal Seeds*

Grain Yield Sampling

At physiological maturity, 0.9 m x 0.9 m samples were taken from each plot via total biomass removal by hand cutting using sickles. Samples were then placed in a drying room at approximately 43° C for at least 24 hours to be dried for sample threshing. Samples were then threshed using a small mechanical thresher, and grain collected and weighed for yield calculation. Post-harvest grain quality was analyzed on whole kernels using near infrared spectroscopy (NIR)

Diode Array NIR analysis Systems model DA 7000 (Kungens Kurva, Sweden) to measure grain moisture and GNC.

Economic Analysis

Economic analysis was conducted using prices \$0.22 kg^{-1} wheat (USDA-NASS, 2020), and \$0.866 kg^{-1} N (urea) (Quinn, 2021). Economic Optimum Nitrogen Rate (EONR) was determined by calculating the profit for each treatment average using the following formula:

$$\boldsymbol{Profit} = \left((\boldsymbol{Yield_{Trt}} - \boldsymbol{Yield_{Check}}) \times \boldsymbol{Price_{Wheat}}\right) - (\boldsymbol{N_{Rate}} \times \boldsymbol{Price_{N}}) \qquad (12)$$

The treatment with the largest profit from each location was deemed the EONR.

Statistical Analysis

Data were analyzed using PROC GLIMMIX procedures (Tukey adjustment, alpha=0.05) using SAS software, Version 9.4 (SAS Institute, Inc., Cary, NC, USA). Figures were produced using package ggplot2 in R (R Core Team, 2020; Wickham, 2016).

Results and Discussion

As location was a significant effector for both yield and GNC ($p<0.001$), statistical analysis was performed by location. While the interaction between two main effects (rate and timing) significantly impacted 14 and 19 locations for yield and GNC, respectively ($p\leq0.031$), main effects were still explored and discussed independently. Nitrogen rate significantly impacted wheat grain yield at 11 locations, and GNC was significantly impacted at 16 locations (Table 3). Winter wheat grain yield and nitrogen concentration were statistically impacted by N timing at 8 locations and 10 locations respectively.

Rate significantly impacted both yield and GNC at 11 of 19 locations, and can be found in Table 3. For all of these locations, the two highest N rates (75% and 100%) provided the highest yields for each location, as to be expected. Yield at Byron 1, Ballagh, Elmwood, and LCB documented a plateau, which suggests that additional N would not increase grain yield. While the highest N rates produced the highest GNC at these locations, an interesting finding from this group of locations was the GNC of the 0 N check was not in the lowest statistical grouping on selected locations: Perkins, El Reno, LCB, Nardin, and Tipton. While not significantly different from the 25% N rate, it was greater than the GNC from that rate, and in the same significance group as higher rates. The authors hypothesize this could be due to early growth supported higher grain yield, but as N became scarce, and N deemed for grain yield became GNC. There are other work suggesting that this could also be due to the dilution effect (Holford et al., 1992).

Rate significantly impacted only GNC at 5 locations, and can be found in Table 3. Yield was not significantly impacted at these locations, which suggests that residual N (Table 1) and mineralization provided enough N for adequate grain production, but did not provide enough to maximize GNC. Capron, Chickasha 1, Lahoma 1, and Chickasha 2 all produced the highest GNC at the 100% N rate treatments. At Chickasha 1 GNC plateaued between the 75 TD and 100 TD treatments at 2.67%, suggesting that GNC was maximized at this location. Granite was significantly impacted by rate for GNC, as it followed similar patterns to other locations, with higher N rates providing higher GNC, yet GNC dropped from 2.51% to 2.32% GNC from the 75 TD to the 100 TD treatment, but not due to application or data collection error.

Rate did not significantly impact either yield or GNC at two locations, Carmen (Figure 9) and Dove (Figure 11). Carmen did not have yield or GNC significantly impacted by N, which suggests researchers overestimated yield potential at this location, and residual N (38 kg N ha^{-1}) was not the limiting factor. Dove location was grazed by wildlife over winter, which authors attribute to variability between treatments. While there were numerical differences in yield, there were not enough differences between treatments to allow for significant differences between rates.

Timing significantly impacted both yield and GNC at three of 19 locations, found in Table 4. For yield, both Dove and Lahoma 2 were negatively impacted by delaying the application of N until top-dress. Again, as Dove location was heavily grazed by wildlife over winter, significance between timing of applications was not found. Lahoma 2 experienced a freeze in early April that disproportionately impacted the top-dress treatment yields over the pre-plant treatments, which may have led to the difference between the timings. This freeze caused major crop damage, leading to yields being so low in the Check and 25 TD treatments that NIR analysis of GNC was not possible. In spite of yield reduction due to top-dress timing, GNC was greatly increased in the top-dress timing over the pre-plant. LCB provided very clear results, with both yield and GNC positively impacted by top-dress applications.

Timing significantly impacted yield at three locations without impacting GNC, found in Table 4. At Chickasha the delayed application of N positively impacted grain yield, while at Byron 2 and El Reno the grain yield was negatively impacted by the delay. Byron 2 top-dress application was applied March 29, 2020, at 121 GDD>0. While the authors did not stage the wheat, previous works have noted that wheat trials grown in the same environment ranged from Feekes 6 - Feekes 10.5 at 120 GDD>0 (Girma et al., 2010). The authors cannot conclude what stage the wheat was at that point, but if in later stages of growth, this could explain loss of yield. Top-dress application at El Reno occurred on March 2, 2020 at 99 GDD>0, and would be 11 days post application before a precipitation event occurred that would have been adequate to incorporate fertilizer (15 mm). All fertilizer applications were applied as ammonium nitrate, and this location had a slightly acidic pH (5.7), so a volatilization was unlikely. Within a 3 weeks of fertilization application, this location did have above average rainfall (100 mm rainfall), which could give cause to leaching, however, not likely. If this location was at a later stage in growth, this could explain why yields decreased with top-dress applications.

Timing significantly impacted GNC without impacting grain yield at six locations, found in Table 4. For each of these locations, GNC was positively impacted by delaying N application until top-dress. This is supported by other work that suggests delaying N into the spring increases GNC at

Timing did not significantly impact either yield or GNC at seven locations: Byron 1 (Figure 1), Capron (Figure 2), Chickasha 1 (Figure 3), Elmwood (Figure 13), Granite (Figure 14), Nardin (Figure 18), and Hobart (Figure 15). At each of these locations, sans Hobart, rate significantly either yield or GNC, yet timing did not negatively or positively impact either. Hobart, as discussed prior, had timing significantly impact GNC, but had variability in stand and environment, leading to authors disregarding statistical differences seen.

Table 3 This table displays the statistical grouping for locations that had treatment effects significant for rate main effect. Statistical grouping was developed from PROC GLIMMIX in SAS 9.4, using Tukey adjustment and alpha=0.05. Treatments with the same letters are not significantly different from one another.

Rate		**Yield** *kg ha^{-1}*					**Grain N** *% N*				
		Application Rate %									
Year	**Site**	**0**	**25**	**50**	**75**	**100**	**0**	**25**	**50**	**75**	**100**
18-19	Byron 1	1952^{D}	3256^{C}	3961^{B}	4548^{AB}	4854^{A}	1.75^{C}	1.79^{C}	1.95^{B}	2.04^{B}	2.25^{A}
	Capron	3211	3685	3687	4199	4180	1.87^{C}	1.89^{C}	2.09^{BC}	2.24^{AB}	2.35^{A}
	Chickasha 1	3094	3212	3423	3464	3144	2.23^{B}	2.22^{B}	2.36^{AB}	2.54^{A}	2.57^{A}
	Lahoma 1	3310	3218	2827	3065	2784	1.89^{B}	2.01^{B}	2.13^{B}	2.16^{AB}	2.45^{A}
	Perkins	1405^{D}	2118^{CD}	2551^{C}	3198^{B}	4379^{A}	2.00^{AB}	1.87^{B}	1.92^{B}	1.95^{B}	2.16^{A}
19-20	Ballagh	3136^{C}	4102^{B}	5258^{A}	5822^{A}	5655^{A}	1.60^{C}	1.59^{C}	1.75^{BC}	1.83^{AB}	1.94^{A}
	Byron 2	3127^{B}	3435^{AB}	4222^{A}	3986^{AB}	3788^{AB}	2.04^{C}	2.19^{C}	2.41^{B}	2.49^{AB}	2.57^{A}
	Byron 3	3103^{B}	3666^{B}	3973^{B}	4944^{A}	5051^{A}	1.78^{B}	1.77^{B}	2.01^{AB}	2.16^{A}	2.30^{A}
	Carmen	2192	1857	2085	1625	2429	2.34	2.35	2.49	2.51	2.54
	Chickasha 2	2863	3480	3474	3491	3866	1.85^{C}	1.91^{C}	2.15^{B}	2.35^{B}	2.61^{A}
	Dove	2737	3359	3812	3245	3307	1.88	2.28	2.17	2.43	2.42
	El Reno	1941^{C}	3235^{B}	3724^{AB}	4055^{A}	3973^{A}	1.74^{BC}	1.61^{C}	1.77^{BC}	1.88^{B}	2.09^{A}
	Elmwood	3624^{C}	4253^{B}	4951^{A}	4683^{AB}	4891^{A}	1.61^{D}	1.73^{D}	1.90^{C}	2.09^{B}	2.25^{A}
	Granite	2495	3226	2714	3058	2773	1.71^{D}	1.95^{CD}	2.19^{BC}	2.46^{AB}	2.56^{A}
	Hobart	2088	2492	2696	3190	2540	2.03	2.02	2.33	2.18	2.09
	Lahoma 2	593^{B}	1552^{AB}	1863^{A}	2398^{A}	2512^{A}	-	1.75	2.11	2.09	2.24
	LCB	1465^{C}	2606^{B}	3711^{A}	4126^{A}	4273^{A}	2.14^{AB}	1.71^{B}	2.04^{AB}	2.19^{AB}	2.26^{A}
	Nardin	1142^{B}	2100^{B}	2827^{A}	2875^{A}	3262^{A}	1.75^{BC}	1.71^{C}	1.95^{BC}	2.24^{AB}	2.43^{A}
	Tipton	1026^{C}	1891^{B}	2529^{A}	2489^{A}	2534^{A}	1.63^{BC}	1.57^{C}	1.83^{BC}	2.18^{AB}	2.32^{A}

Table 4 This table displays the statistical grouping for locations that had treatment effects significant for timing main effect. Statistical grouping was developed from PROC GLIMMIX in SAS 9.4, using Tukey adjustment and alpha=0.05. Treatments with the same letters are not significantly different from one another.

Timing		**Yield** *kg ha^{-1}*		**Grain N** *% N*	
		Timing			
Year	**Site**	**Pre**	**Top**	**Pre**	**Top**
2018-2019	Byron 1	3989	4269	1.95	2.05
	Capron	4155	3671	2.07	2.22
	Chickasha 1	3486	3139	2.38	2.49
	Lahoma 1	3175	2755	2.08^{B}	2.33^{A}
	Perkins	2840	3210	1.89^{B}	2.05^{A}
2019-2020	Ballagh	4934	5366	1.68^{B}	1.88^{A}
	Byron 2	4121^{A}	3569^{B}	2.38	2.47
	Byron 3	4309	4549	1.91^{B}	2.23^{A}
	Carmen	1820	2120	2.41^{B}	2.53^{A}
	Chickasha 2	3356^{B}	3834^{A}	2.22	2.33
	Dove	3535^{A}	3277^{B}	2.20^{B}	2.57^{A}
	El Reno	3993^{A}	3548^{B}	1.78	1.92
	Elmwood	4683	4692	1.98	2.01
	Granite	3022	2880	2.41	2.21
	Hobart	2734	2758	2.12	2.19
	Lahoma 2	2447^{A}	1591^{B}	1.84^{B}	2.62^{A}
	LCB	3197^{B}	4026^{A}	1.82^{B}	2.23^{A}
	Nardin	2993^{A}	2539^{B}	1.90^{B}	2.27^{A}
	Tipton	2484	2237	1.76^{B}	2.15^{A}

Rate

Across 19 locations total locations for this study, 11 locations were significantly impacted by rate. Of the 11, five locations provided evidence that yield was maximized by a rate within the treatment structure. These are: Byron 1, 75% N rate; Ballagh, 100% N rate; Elmwood, 50% N rate; LCB, 75% N rate; Tipton, 50% N Rate. As discussed prior, 100% N rate treatments were determined by the authors, using regional yield potential of the area, considering the productivity of the location, environmental parameters, and historical yield. There were six locations that did not have yield maximized by the rate treatments.

Across 19 locations, GNC was significantly impacted by N rate at 17 locations (including Lahoma 2), and four were found to maximize grain N (Table 3). At all of these locations, yield was either maximized as well (LCB), yield was non-responsive (Chickasha 2, Byron 2), or yield was reduced due to late freeze (Lahoma 2). For LCB, Chickasha 2, and Byron 2, this was due to excess N available late in the season, leading to increase in grain N. Lahoma 2 could also be considered to be due to excess N, as the freeze limited yield, therefore, allowing more N to be available for grain accumulation. The treatments that maximized grain N were 75% N rate or higher, showing that only the higher N rates will provide higher/maximized grain N, even when yield is maximized at lower rates, or non-responsive.

Timing

Across 19 locations, seven had yield significantly affected by timing. Two of these locations (Chickasha 2, LCB) had higher top-dress yields than pre-plant, and the other 5 had higher pre-plant yields than top-dress. Previous works have shown that delaying N maintained or increased yield in winter wheat (Souza, 2018), and the data from this trial supports those works. The five locations that had higher yield at the earlier timing had evidence as to why yield was lost. Two of the locations (Byron 2, and El Reno) were applied later in the season/growth stages of wheat, and did not receive rainfall in enough time for that fertilizer to be incorporated and available for the crop. Dove field had grazing pressure in the winter months, and the plots that received N in the fall recovered better than the later applied fertilizer. Lahoma 2 had a freeze late in the season that harmed the smaller wheat (that without N in the fall) more than the larger wheat. Nardin had weed pressure that was higher in the plots that did not receive any N in the fall. Two of these locations had un-foreseen circumstances that led to lost yields in the spring, but the others could have been avoided by making the correct decisions as to when N is applied.

Across all locations with GNC significantly impacted by timing (10 locations), GNC was increased when delayed into the spring. At four of these, grain N was actually maximized by delaying N till the spring. For all other locations, GNC was considered no different between timings. This provides evidence that delaying N application till in-season will increase grain N concentration.

Nitrogen rate recommendation

Oklahoma State University recommendation for yield includes 0.03 kg N ha^{-1} per 1kg ha^{-1} increase in yield, subtracting the amount of N in the soil derived from the soil test. This requires a producer to have a yield goal for their field. Historically, the yield goal is recommended to be a 5 year average of the field, with an additional 20% (Raun et al., 2017). Yield goals were not taken at any location, so recent yield averages by county were used (USDA-NASS, 2020), plus 20%. Throughout the rest of the manuscript the N rate determined by yield goal and soil test will be represented by $N_{YieldGoal}$.

Using this information, we can assess OSU recs compared to the locations that maximized yield. A limitation of this study is that the accuracy of recommendations due to treatment structure only including four rates. Researchers sacrificed the total number of potential rates (providing closer approximation of N rate) in order to have more locations and two timings. Therefore, recommendations can only be assessed of their accuracy looking at the next rate up. For example, if recommendations would have applied 50 kg N ha^{-1}, and the treatment structure only included increments of 34 kg N ha^{-1}, the 67 kg N ha^{-1} rate would be the treatment that would be considered to have maximized yield.

Table 5 displays the yield goal calculated from county average, plus 20%, the subsequent $N_{YieldGoal}$ to reach that yield goal derived from yield goal and soil test NO_3-N, the Achieved Yield, N rate to reach achieved yield based on OSU recommendations ($N_{Achieved}$), as well the N rate from this study that maximized yield at that location (N_{Max}).

Table 5 The Soil Test NO_3-N, Yield Goal based upon county average of each location, plus 20% increase, the N rate to reach the yield goal ($N_{YieldGoal}$), the Achieved Yield, the N rate required to reach the Achieved Yield ($N_{Achieved}$), and the N rate in this study that maximized yield (N_{Max}). Both $N_{YieldGoal}$ and $N_{Achieved}$ were calculated using Oklahoma State University recommendations of 0.03 kg N ha^{-1} per 1 kg ha^{-1} yield increase. Locations included were those that maximized yield.

Location	**NO_3-N**	**Yield Goal**	**$N_{YieldGoal}$**	**Achieved Yield**	**$N_{Achieved}$**	**N_{Max}**
			kg ha^{-1}			
Ballagh	9	2500	66	6114	174	134
Byron 1	57	1662	0	4883	89	112
Elmwood	54	2275	14	4981	96	101
LCB	11	3146	83	4484	123	134
Tipton	6	2598	72	2893	81	101

Based on $N_{YieldGoal}$ derived from historical data, no location would have maximized yield within the range of treatments, as on average the historical yield goal was 2200 kg ha^{-1} less than achieved yield. However, if $N_{YieldGoal}$ was based on achieved yield (see $N_{Achieved}$), each location would have maximized yield. Raun et al. (2017) noted that yield goals based on historical yield of the same field were not correlated with ensuing season yield, and this is supported by our data.

Conclusion

The objective of this trial was to investigate the effect of N rate and timing on winter wheat grain yield and grain N values across varying environments across the state of Oklahoma. For this reason, more rates and multiple timings were sacrificed in order to increase range of locations and environments. This did not allow this trial to accurately deduce the best rate and timing, however, it does allow us to see how different environments respond to N rate and timing.

As to be expected, the higher N rates provided the highest yield and grain N values at responsive locations. Yield goal derived N recommendations were not found to be accurate, due to only one of 5 locations that maximized yield had yield goals accurate within 90% of achieved yield. Yet, post hoc analysis of those locations that maximized yield provided support for OSU yield based recommendations (0.03 kg N ha^{-1} per 1kg ha^{-1} increase in yield, minus soil test NO_3-N), as recommendations would have included enough N to maximize yield. This suggests that if achieved yield was accurately predicted for each location, the N fertilizer requirements could be determined.

At four of the locations that maximized yield, grain N was also maximized by applying highest N rates. Oklahoma State University currently does not employ any recommendations for grain N content, yet in some years, many producers could receive a premium for higher grain N content. For this reason, there could be work done in the future to develop N recommendations for increased grain N.

Across the 14 locations where N application impacted yield, timing significantly impacted yield at 7, with only two locations providing higher yields with a top-dress application. The other locations had reduced yields due to unforeseen circumstances (grazing, late freeze), or late incorporation and availability of N fertilizer, which lends to the challenges a producer may encounter. Previous work has shown that by delaying N into the spring, yields could be maintained, or in some cases, increased. This study echoes that as well, as long as fertilizer was available to the crop in a timely fashion.

The author's hypothesis for this project was that N rate and timing applications would perform similar in varying environments across the state of Oklahoma, and the results provided support for this hypothesis. Timing and rate were found to follow similar patterns across all environments for this trial. This provides support that yield prediction is a valuable tool that could improve the efficiency at which winter wheat producers apply N fertilizer.

CHAPTER IV

USE OF ON-FARM NITROGEN TRIALS TO UPDATE SENSOR BASED NITROGEN RATE CALCULATOR USING GREENSEEKER SENSORS

Introduction

Utilizing optical sensors to estimate N fertilizer recommended rates has been implemented in Oklahoma since their inception in Raun et al. (2002). Over time, those algorithms have been updated to reflect new data collected from research trials. However, those trials are set up on research stations majority being located in central Oklahoma, where the climate and environment can be much different than other large wheat producing areas.

The objective of this chapter is to assess current sensor based nitrogen recommendation calculator (SBNRC) algorithm via on on-farm trials, and look for opportunity to refine the SBNRC. Authors hypothesize that adding a regional component to the current model could provide more tailored recommendations for producers. The authors also hypothesized that due to previous studies on worldwide NUE_N (Omara et al., 2019), NUE would be the component of SBNRC that, if refined, would provide more accurate N rate recommendations.

Materials and Methods

Study area

This portion of this dissertation utilizes data reported in Chapter 3. The experimental design of this trial was randomized complete block design (RCBD) with a 2 x 4 factorial design structure; 2 timings (pre-plant and in-season fertilizer application, applied prior to Feekes 5 growth stage) by 4 rates (25%, 50%, 75%, 100% yield potential rate) applied as ammonium nitrate (AN, 34-0-0), with 4 replications. Site specific rate was determined using the yield potential of the area, considering the productivity of the location, environment parameters, and historical yield. The 100% rates were determined using the OSU recommendations of 2.24 kg ha^{-1} N per 67.25 kg ha^{-1} wheat. Plot sizes were 1.8 m x 1.8 m, with 1.2 m alleys between repetitions. This study was implemented and managed to harvest at a total of 19 locations across 4 climatological zones (found in Table 2, and Figure 17); 5 locations in the 2018-2019 growing season, and 15 locations in the 2019-2020 growing season.

Soil Analyses

Composite pre-plant soil samples were taken by location (0-15 cm) for background soil test information. Samples were dried at 65°C overnight and ground to pass a 2 mm sieve prior to extraction and analysis, conducted following methods set by Crouse et al. (2014). The pH was measured by using a combination electrode within a 1:1 ratio of soil to water suspension. Nitrate-N was extracted using a 1M KCl extraction solution with 2 g of soil to 20 mL of solution with 15 minutes of shaking time. Nitrate-N was then determined by automated colorimetric flow-injection analysis (Lachat Quickchem 8000, Loveland, CO). The Mehlich-3 (M-3) method was used to find extractable P, K, Ca, and Mg, by extracting 2 g of soil with 20 mL of M-3 solution and shaking for 5 minutes. Exchangeable S was found by mixing 10 g of soil with 25 mL of 0.008M calcium phosphate solution and shaking for 30 minutes. Concentration of P, K, Ca, Mg, and S in the extracts were determined with an inductively coupled plasma atomic emission spectrometer (ICP-AES). Organic Matter (OM) was determined using dry combustion methods. Soil chemical and nutrient analysis data is presented in Table 6.

Table 6 Soil Test analyses for each location. Values provided are pH, NO_3-N and SO_4-S (kg ha^{-1}), Soil test Phosphorus (STP), Soil Test Potassium (STK), Calcium and Magnesium (ppm), and Organic Matter (OM, %).

Year	**Location**	**pH**	**NO_3-N**	**SO_4-S**	**STP**	**STK**	**Ca**	**Mg**	**OM**
			kg ha^{-1}		*mg kg^{-1}*				*%*
2018-2019	Byron 1	6.8	57	7	22	225	853	312	1.4
	Capron	6	-	-	10	236	1430	633	1.1
	Chickasha 1	5.9	50	52	33	143	1536	511	-
	Lahoma 1	7.1	9	2	7	143	1300	542	-
	Perkins	7.4	3	2	26	142	788	184	-
2019-2020	Ballagh	7.2	9	25	23	135	2860	324	3.1
	Byron 2	5.5	68	9	17	197	696	320	1.3
	Byron 3	5.6	66	9	20	230	853	264	1.5
	Carmen	6.5	38	25	6	295	1469	503	-
	Chickasha 2	6.9	2	8	7	235	2394	963	2.1
	Dove	6.3	7	10	31	131	974	399	1.1
	El Reno	5.7	5	16	63	174	1610	429	2.0
	Elmwood	7.6	54	11	66	567	3890	265	2.3
	Granite	5.3	21	13		256	1446	269	1.3
	Hobart	7.8	13	4	6	390	4007	463	2.1
	Lahoma 2	6.1	9	13	7	207	3155	1202	1.4
	LCB	5.7	11	36	20	607	2545	1002	2.1
	Nardin	5.6	128	17	7	188	1749	433	2.4
	Tipton	7.2	9	7	22	225	853	312	1.4

Vegetation Reflectance Data Collection and Analysis

Reflectance data of each plot was collected as close to Feekes 5 growing stage for each location as possible for the purpose of the SBNRC calculations. The SBNRC calculation requires NDVI values from a farmer practice strip (FPS) and N-Rich Strip. For this trial, NDVI collected from the top-dress 100% N rate treatment (prior to application) was considered FPS, and the pre-plant 100% N rate treatment was considered the N-Rich Strip. These values were used to calculate the response index (RI_{NDVI}). This time coincides with 80-110 GDD>0, the time period where yield prediction has been found to be most accurate for NDVI (Sembiring et al., 2000). NDVI values were obtained with the Greenseeker® (Trimble Inc, Sunnyvale, CA) sensor. The Greenseeker® sensor is an active sensor utilizes light wavelengths in the red and NIR spectrum (660 and 780 ± 10nm) to measure light reflectance, measured in NDVI, or normalized difference vegetative index. Data was collected with the sensor head held approximately 50 cm above wheat canopy and sensor carried over the center of each plot.

Grain Yield Sampling

At physiological maturity, 0.9 m x 0.9 m samples were taken from each plot via total biomass removal by hand cutting using sickles. Samples were then placed in a drying room at approximately 43° C for at least 24 hours to be dried for sample threshing. Prior to threshing, total biomass samples were weighted (data not shown), then threshed using a small plot thresher, and grain was measured for data collection. Post-harvest grain quality was analyzed using near infrared spectroscopy (NIR) Diode Array NIR analysis Systems model DA 7000 (Kungens Kurva, Sweden) to measure grain moisture and grain N concentration.

Statistical Analysis

Statistical modeling was conducted using trend analysis software in Microsoft Excel, and figures were produced using package ggplot2 in R (R Core Team, 2020; Wickham, 2016).

Results and Discussion

The objective of this chapter was to evaluate OSU's current SBNRC using a geographically diverse set of on-farm N rate and timing studies. The secondary aspect of this project was to propose refinements to the SBNRC that could potentially improve the calculator's precision.

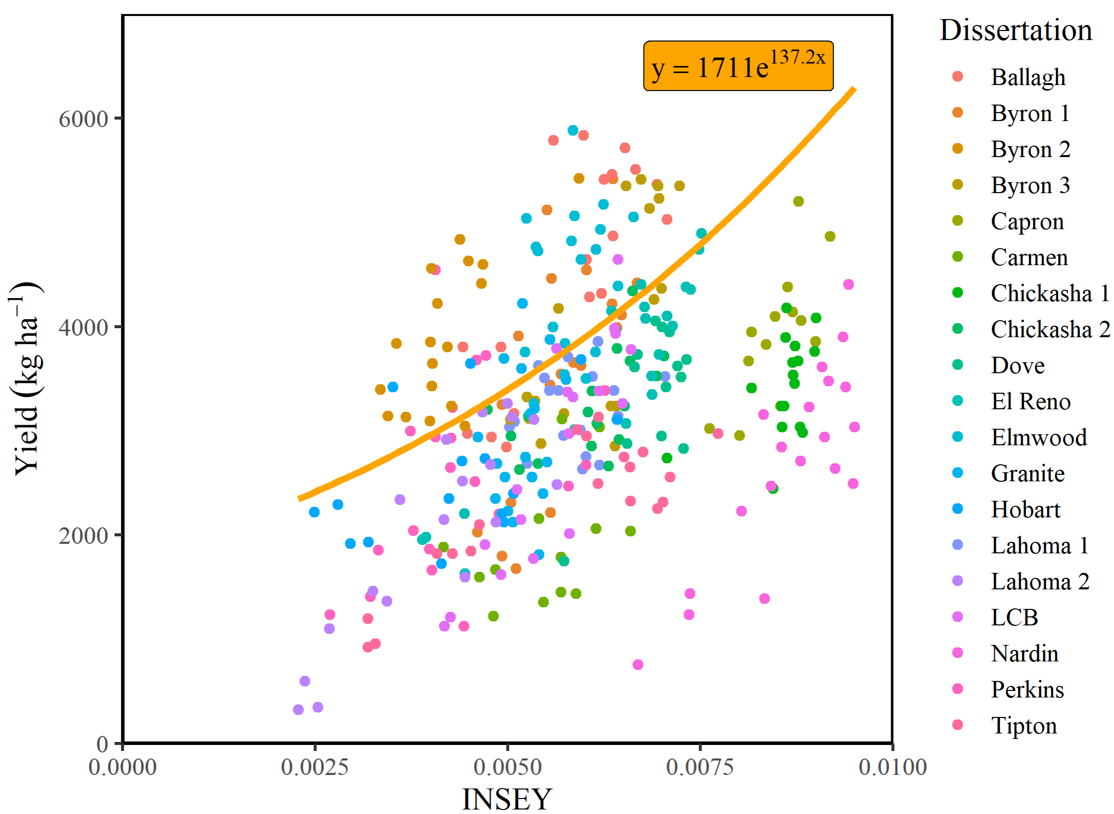
INSEY, Yield Potential without added Nitrogen (YP_0)

As discussed in the review of literature, the first step in the SBNRC is the INSEY calculation, seen below.

$$INSEY = \frac{NDVI}{GDD > 0} \quad (13)$$

The INSEY variable is calculated by dividing the NDVI from N-rich strips by GDD>0, or days where average ambient temperature is above 4.4° C, a threshold set for small grain crops, where growth occurs. This value represents a growth factor, in growth (NDVI) by day (GDD>0). The current yield prediction model is built by plotting INSEY against achieved yield, with a positive shift one standard deviation to reflect yield potential, from over 20 years of long-term fertility wheat trials (Raun et al., 2005). Figure 20 below displays INSEY and yield from this dataset, as well as the current OSU yield prediction model. As the yield potential model is shifted one standard deviation above the fitted model, statistically, this would mean that ~33.3% of the data would fall above the line, however, only 23% of this dataset falls above the model line.

Figure 1 INSEY from this dataset plotted against achieved yield (kg ha^{-1}). Also included is the current yield prediction model (orange line) for comparison to INSEY data.



Response Index (RI)

The next component for evaluation of the current SBNRC model is the response index (RI). Response index refers to ratio between values taken from the FPS and N-rich strip; either from yield (RI_{Yield}) or NDVI (RI_{NDVI}). In the original SBNRC model, YP_0 was multiplied by RI_{NDVI}, as RI_{NDVI} and RI_{Yield} were found to be highly correlated, however, Mullen et al. (2003) established an adjustment factor to RI_{NDVI}, to reflect differences in RI_{NDVI} and RI_{Yield} in their studies. The RI calculations can be seen below.

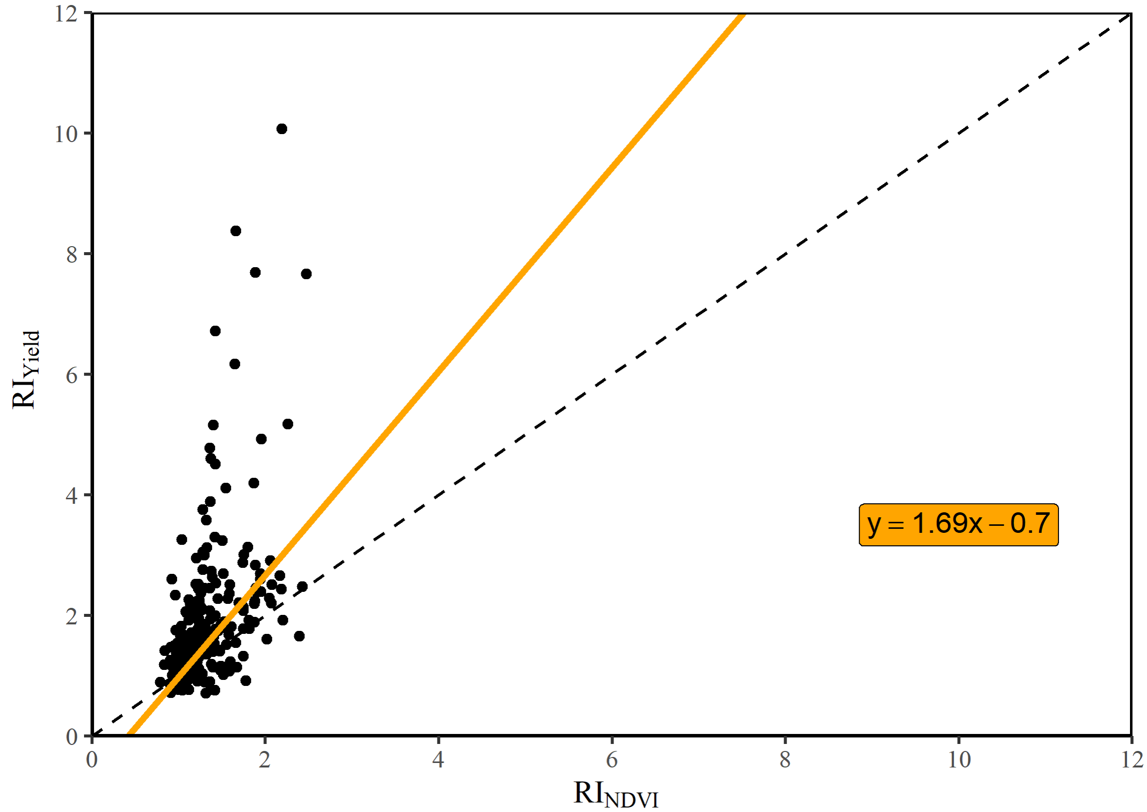
$$\boldsymbol{RI_{NDVI} = \frac{NDVI_{N\,Rich}}{NDVI_{0N}}} \quad (14)$$

$$\boldsymbol{RI_{Yield} = \frac{Yield_{N\,Rich}}{Yield_{0N}}} \quad (15)$$

$$\boldsymbol{RI_{Adjust} = 1.69 \times RI_{NDVI} - 0.70} \quad (16)$$

Figure 21 below displays the RI_{NDVI} and RI_{Yield} from this data, as well as the current RI_{Adjust} line utilized by OSU. While some points with lesser RI_{Yield} values are close to the OSU adjustment line, it can be seen that the line does not fit this dataset either.

Figure 2 RI_{NDVI} plotted against RI_{Yield}. The dotted line represents the 1:1 relationship of RI_{Yield} and RI_{Sensor}. The orange line represents the current RI adjustment equation.



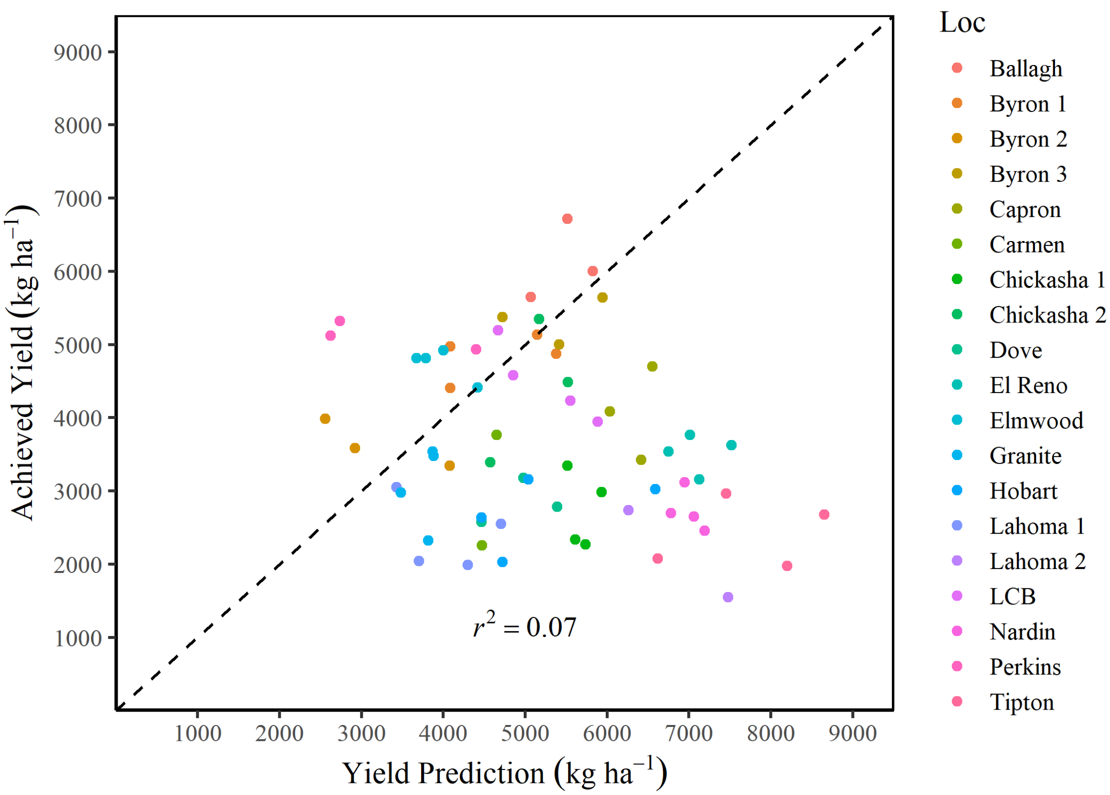
Yield Potential with Nitrogen (YP_N)

The yield prediction portion of the SBNRC utilizes both the YP_0 and RI_{Adjust} calculations. Yield prediction of area with nitrogen (YP_N) is calculated with the calculation below.

$$YP_N = YP_0 \times RI_{Adjust} \quad (17)$$

The INSEY from the FPS is used in the INSEY model to provide a predicted yield, YP_0, or the yield prediction if 0 N is applied. Then, YP_0 is multiplied by RI_{Adjust} to provide an estimate of YP_N, or yield prediction if N is applied. This provides a yield prediction to be used for N rate calculation. Figure 22 displays the YP_N yield potential values plotted against the achieved yield from the 100 TD treatment (up to 4 repetition per location).

Figure 3 The correlation between predicted and achieved yield. This yield prediction is derived from the current algorithm employed by Oklahoma State University. Each point represents one repetition within each location. The dotted line represents the line at which $Yield_{Predicted} = Yield_{Achieved}$.



In-season yield predictions to be seen as an assessment of the crops maximum yield potential, based upon current circumstances. Yet, post sensing stressors can occur (freeze, drought, disease, etc.), and are expected to occur, that will negatively impact the crops achieved grain yield. Therefore, the authors would expect that the yield potential prediction would be greater than the achieved yield in most cases. Yield prediction derived from NDVI across the trial provided no correlation with the achieved yield from those plots ($r^2 = 0.07$), but still performed as expected, with achieved yield falling below predicted yield.

Nitrogen Rate Calculation

The final portion of the SBNRC model is the calculation of the recommended N rate. The calculation is found below.

$$\boldsymbol{Rate_N = \frac{(YP_N - YP_0) \times PNG}{NUE_N}} \qquad (18)$$

Where PNG is the total grain N (assumed as 0.0239), and NUE_N is the N use efficiency.

Table 7 displays each location, with the N rate recommended by the SBNRC, the EONR (economically optimum N rate), predicted yield, achieved yield, the RI_{NDVI} and the calculated NUE for each plot.

This table (Table 7) displays how each component within the SBNRC algorithm is compared to the achieved output. Differences in SBNRC N rate and EONR ranged from 10 to 104 kg N ha^{-1}, with an average difference of 49 kg N ha^{-1}, and a median value of 37 kg N ha^{-1} below EONR. On average SNBRC was under-applying EONR, with only 6 of 19 locations having a higher SBNRC than EONR. Differences in Predicted Yield and Achieved Yield ranged from 84 to 5495 kg ha^{-1}, with an average difference of 1845 kg ha^{-1}, and median difference of 1570 kg ha^{-1} below.

Table 7 The SBNRC (Sensor Based Nitrogen Rate Calculator) recommended Rate, EONR (Economic Optimum Nitrogen Rate), the average achieved yield of the top-dress 100% N (100 TD) rate treatment, the average predicted yield for each location, the Response Index from the NDVI and Yield, and NUE as a percentage based on the EONR treatment. NUE in the SBNRC is assumed as 70% NUE.

Location	SBNRC Rate	EONR	Yield Prediction	Achieved Yield	RI_{Adjust}	RI_{Yield}	NUE
	kg N ha^{-1}		kg ha^{-1}				%
Ballagh	73	134	5482	6114	1.66	1.92	53
Byron 1	47	84	4756	4840	1.42	2.48	83
Byron 2	17	67	3008	3634	1.12	1.18	34
Byron 3	61	134	5427	5331	1.51	1.72	40
Capron	43	112	6310	4065	1.25	-	18
Carmen	24	0	4713	3007	1.18	-	0
Chickasha 1	6	84	5692	2730	1.03	-	12
Chickasha 2	53	134	5196	4405	1.44	1.50	27
Dove	30	67	4823	2843	1.23	1.04	43
El Reno	141	101	6883	3516	2.40	1.83	48
Elmwood	8	67	4132	4732	1.04	1.31	48
Granite	15	34	3648	3076	1.13	1.24	26
Hobart	91	101	5126	2708	2.07	-	30
Lahoma 1	17	0	3974	2404	1.08	-	0
Lahoma 2	152	134	6522	2138	2.86	6.32	28
LCB	64	134	5550	4484	1.58	3.26	54
Nardin	88	67	6938	2728	1.59	2.81	58
Perkins	8	112	4869	5116	1.01	3.63	79
Tipton	172	101	7915	2420	2.87	2.25	34

'-' *in the RI_{Yield} column denotes location where N application did not significantly impact yield*

predicted yield. On average, Predicted Yield was higher than Achieved Yield, with only 5 locations having higher Achieved Yield than Predicted Yield. Differences in RI_{Adjust} and RI_{Yield} ranged from 4 to 259% difference, with a median difference of 15% below RI_{Yield}. On average, RI_{Adjust} was less than RI_{Yield}, with only 6 locations within 20% of RI_{Yield}. NUE for locations that would have required N based on EONR ranged from 12 to 83%, with an average NUE of 42%.

OSU currently utilizes 70% as the value used in the SBNRC algorithm, but only 5 of 19 locations fell within 20%.

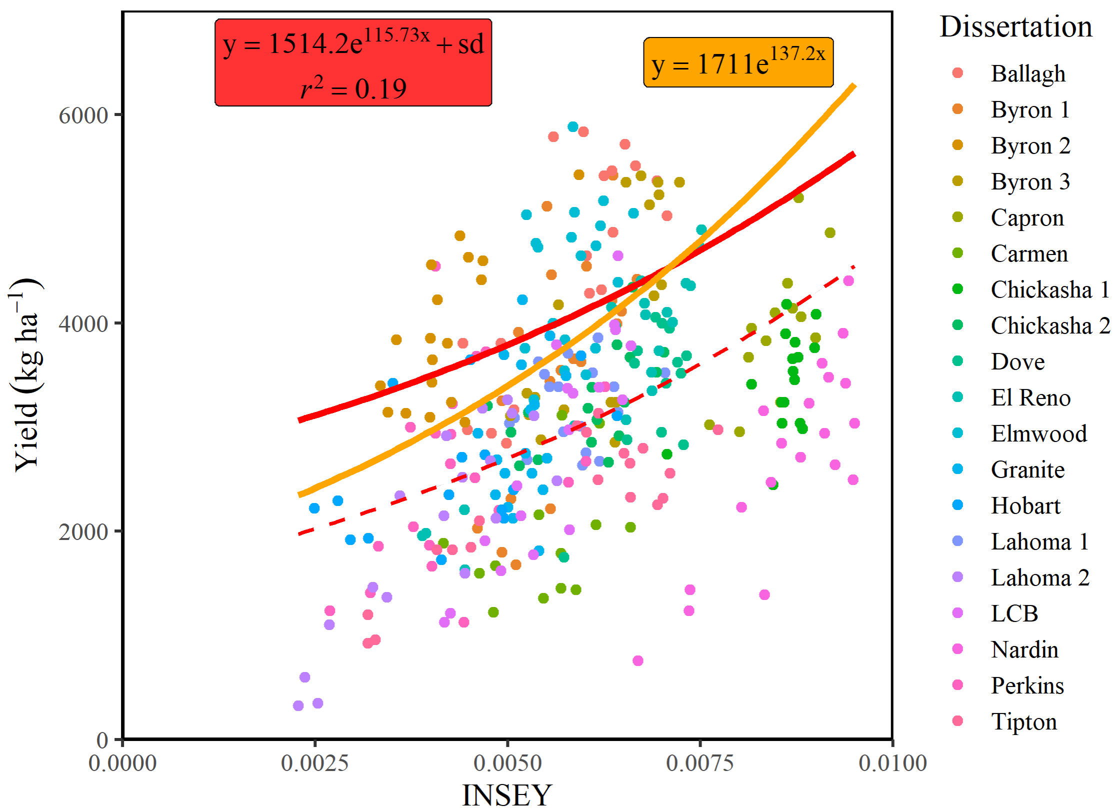
Perkins provided very interesting results, as that there was no difference in NDVI values of the FPS and N-Rich Strip at top-dress application and sensing. Reflectance data (FPS: 0.55, N Rich Strip: 0.53) was collected at this location on April 3, 2019, with 106 GDD>0. Yet this location did result in a significant response to applied N fertilizer with a RI_{Yield} of 3.53. This is a limitation of the current in-season N management scheme, in the fact that sometimes response may be delayed further than expected and yield still be recovered.

It can be surmised that there are areas in which the SBNRC can be refined in order to produce more accurate recommendations for producers as discussed. The following sections will offer opportunities for changes to address this objective.

INSEY Yield Potential Model

In order to build a yield prediction model for this dataset, the same steps taken to build the original model was used. The INSEY which was derived from the NDVI values from all pre-plant fertilizer application treatments was plotted against the achieved yields, and shifted up one standard deviation, to reflect yield potential. Figure 23 displays the model built from this dataset. Plots that had greater INSEY, meaning that they were larger wheat at sensing, had greater power on the model, skewing the slope. This allows this model to be less effected by the size of the wheat than the current OSU yield prediction model.

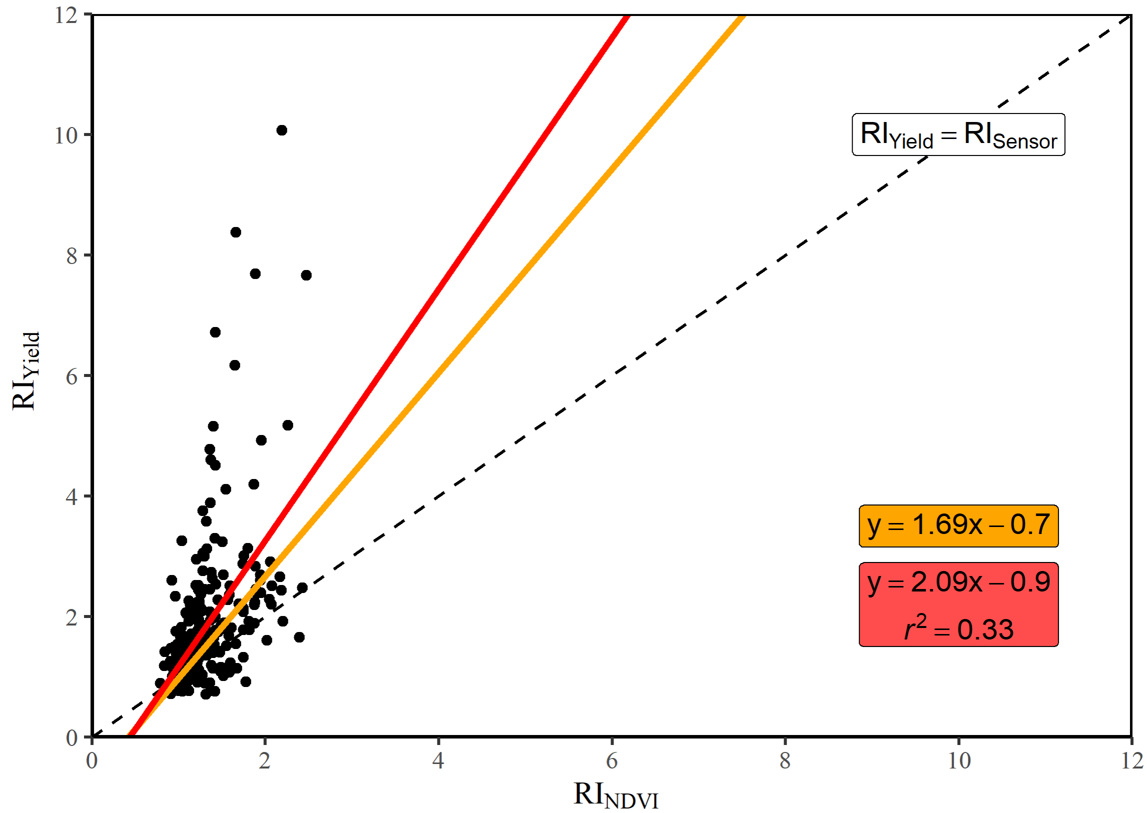
Figure 4 Yield prediction (YP_0) model built from the data in this on-farm trial. The red dotted line represents the model that fits the dataset, and the solid red line represents that line transformed up one standard deviation, in order to account for maximum potential yield. The solid orange line represents the current OSU model for yield prediction.



RI adjustment Equation

The RI_{Adjust} is used to reflect the relationship between RI_{NDVI} and RI_{Yield}. The relationship between $RI_{Harvest}$ and RI_{NDVI} can be explored using data collected from this trial. Figure 24 displays that plotted comparison between RI_{NDVI} and RI_{Yield}. The slopes between the two lines are similar, however, the equation derived from this data takes more into account areas with large RI_{Sensor} and RI_{Yield}. This occurs mainly to areas with very little residual N in the soil and can show a large difference between the FPS and the N Rich Strip. The locations that had the largest RI_{Sensor} and RI_{Yield} were locations with less than 10 kg N ha^{-1} in the topsoil.

Figure 5 Comparison of Response Index Values. The dotted line represents the 1:1 relationship of RI_{Yield} and RI_{Sensor}. The orange line represents the current RI adjustment equation, and the red line represents the RI adjustment equation for this dataset.



NUE

For almost two decades, NUE for this SBNRC N rate equation was set to 50%, meaning that only 50% of the applied N would be utilized by the plant (Raun, 2018). This value was increased in 2018 to 70% NUE, to account for perceived increase in application efficiency by producers (Raun, 2018). Figure 25 displays a histogram of NUE across this project, for locations that had EONR>0.

NUE was calculated across this trial using the EONR rate, not rate that performed highest statistically, as producers would be more interested in the economic optimum yield, not in particular the statistically highest rate. For locations that EONR was not zero, the average NUE was 42%. This suggests that 70% NUE value set by current OSU SBNRC is too high to be used for N rate calculations, reducing the amount of N applied to each field, and in turn, increases risk of not achieving EONR.

Figure 6 Histogram of calculated NUE across this trial, for locations that had EONR (Economic Optimum N Rate) greater than 0. The vertical dotted line represents the mean NUE across the trial, at 42%. This figure displays that while current SBNRC (Sensor Based Nitrogen Rate Calculator) utilizes 70% NUE in its calculations, this trial suggests that that value is too high.

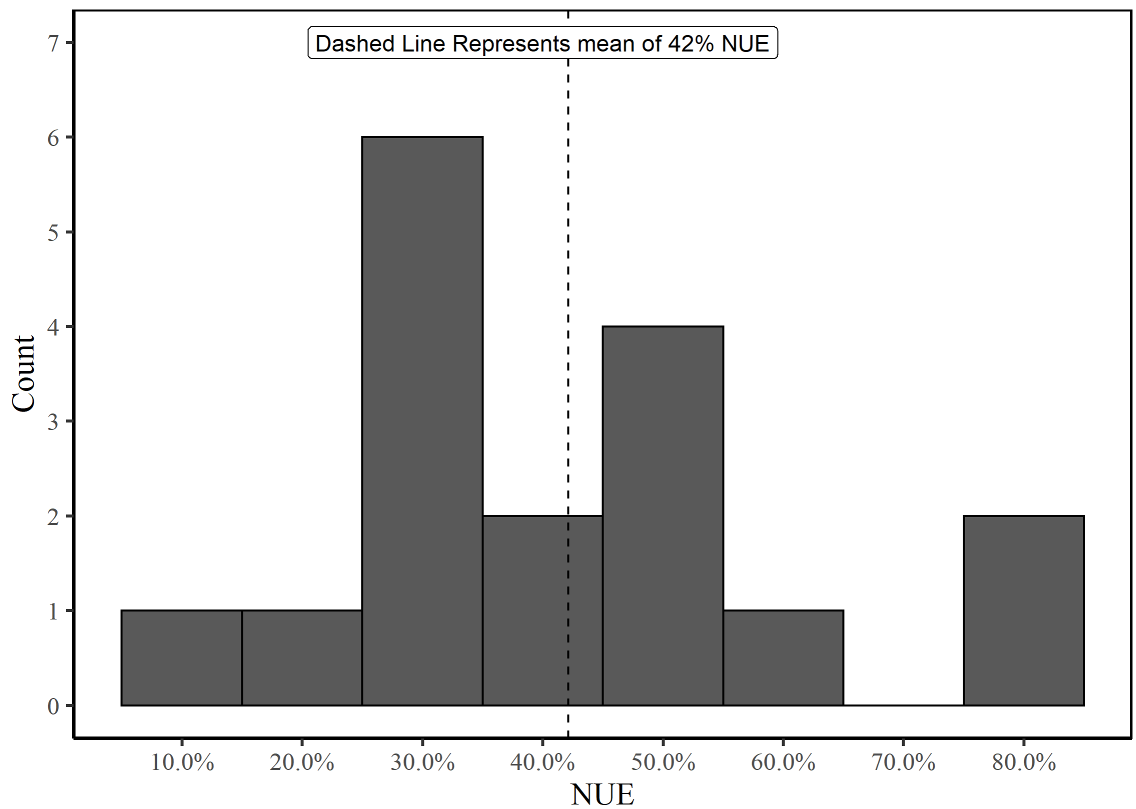


Table 8 displays how adjustments to NUE impact the N rate recommendations, as well as the RI adjustment factor developed from this dataset compares to the current RI_{Adjust} and RI_{Yield}.

Table 8 SBNRC (Sensor Based Nitrogen Rate Calculator) recommended Rate, EONR (Economic Optimum Nitrogen Rate), the average achieved yield of the 100% N rate treatment, the average predicted yield for each location, the Response Index from the sensor, and NUE as a percentage based on the EONR treatment.

Location	SBNRC Rate	SBNRC New YP	SBNRC RI	SBNRC NUE 42	SBNRC YP, RI, NUE42	EONR
			kg N ha^{-1}			
Ballagh	73	84	115	125	192	134
Byron 1	47	54	82	79	136	84
Byron 2	17	15	35	21	59	67
Byron 3	61	68	102	104	170	134
Capron	43	42	89	73	149	112
Carmen	24	26	56	40	94	0
Chickasha 1	6	5	45	10	75	84
Chickasha 2	53	58	90	88	150	134
Dove	30	33	67	53	112	67
El Reno	141	167	195	236	326	101
Elmwood	8	6	33	10	56	67
Granite	15	16	41	24	68	34
Hobart	91	116	132	154	219	34
Lahoma 1	17	11	39	17	65	0
Lahoma 2	152	197	205	254	342	134
LCB	64	75	106	111	176	134
Nardin	88	89	140	147	233	67
Perkins	8	0	22	0	37	112
Tipton	172	211	232	287	386	101
Average Diff.	***-29***	***-21***	***8***	***9***	***95***	**-**
Median Diff	***-37***	***-34***	***-2***	***-10***	***64***	**-**

Evaluating the original SBNRC N rate (using 70% NUE), differences in SBNRC N rate and EONR ranged from below EONR 104 kg N ha^{-1}, to above by 71 kg N ha^{-1}, with an average and median difference of 29 kg N ha^{-1} 37 kg N ha^{-1} below EONR. On average SNBRC was under-applying EONR, with only 6 of 19 locations having a higher SBNRC than EONR.

Adjusting the SBNRC with the RI adjustment provided a range of differences in SBNRC and EONR from below EONR 90 kg N ha^{-1} to above 131 kg N ha^{-1}, with an average application above EONR by 8 kg N ha^{-1}, and median below EONR by 2 kg N ha^{-1}. Eight of the 19 locations would have received applications above EONR using this adjusted component.

Utilizing the NUE adjustment (42% NUE) provided a range of differences from below 112 kg N ha^{-1}, to above EONR 186 kg N ha^{-1}, with an average application above EONR by 9 kg N ha^{-1}, and median application below EONR by 10 kg N ha^{-1}. Seven locations would have received applications above EONR using this adjustment.

Appling the YP model derived from this dataset in the SBNRC equation provided a range of differences from 113 kg N ha^{-1} below EONR to 110 kg N ha^{-1} above EONR, with an average and median difference of 21 kg N ha^{-1} and 34 kg N ha^{-1} below EONR. Seven locations would have received applications above EONR using this adjustment.

Combining all proposed adjustments into the SBNRC N rate provided a range of differences from 71 kg N ha^{-1} below EONR to 373 kg N ha^{-1} above EONR, with an average and median difference of 95 and 64 kg N ha^{-1} above EONR. There were only 3 locations in which this N rate did not apply above EONR.

Each modification of the SBNRC improved the accuracy of the N rate. $SBNRC_{RI}$ more often under applied N, but had 12 locations within 40 kg N ha^{-1} of EONR, and had the median difference closest to 0, meaning that on average, this adjustment should provide precise recommendations. Both $SBNRC_{NUE\ 42}$ and $SBNRC_{YP}$ had 8 and 7 locations within 40 kg N ha^{-1}, respectively, however, when wrong, had with great differences in applications. Combining all adjustments significantly increased total recommended N rates to a level of over-applying by 95 kg N ha^{-1}. The author's hypothesis was that NUE would provide the greatest impact to the SBNRC rate, yet, did not increase accuracy or precision across the dataset. Utilizing the new RI_{Adjust} provided more accurate recommendations across this dataset.

Conclusion

This project included data from a diverse set of environments, soil profiles, moisture regimes, varieties, and two years. The author's hypothesis was that SBNRC could possibly be refined by adding a regional component to the current model can provide more tailored recommendations for producers. However, the data collected from locations across different climatological zones in Oklahoma could not provide any patterns or relationships seen between regions, rejecting the hypothesis. The author's hope was that this broad selection of data would allow a robust dataset in which an accurate model could be built for the entire state, since a region component was not possible.

Refinements suggested throughout the discussion mention the independent components of SBNRC to be made. While the authors hypothesized that NUE would be the component that would provide more accurate N rate recommendations if adjusted, the results displayed that the RI_{Adjust} was the component that provided the greatest potential for improvement. NUE was found to be variable across all locations, so adjusting that value would not fit all locations. Understanding the relationship between RI_{NDVI} and RI_{Yield} across many years and locations could provide results that could be applied to all locations. The authors hypothesize that NUE could be the component that could benefit from a regional component in future studies.

While there were some instances of inaccuracies, the proposed model provided similar, if not more accurate, results for this collection of data than the current SBNRC model. The authors understand that perfection is not possible, and increasing accuracy is the goal. The authors set out to refine the current SBNRC due to it being built from data limited by the space due to fewer environments from the trials. Yet, the current SBNRC model has been developed and updated over time, with 23 years of wheat trials, with at least 2 trials a year, cumulatively at least 75 site-years of data. The proposed model is conversely limited by time, while not necessarily limited by space, as it comprised of 19 locations over two years (5 in 2018-2019, 14 in 2019-2020). The proposed model currently does not have enough years of data to be robust enough to over time provide accurate yield prediction in years different from the past two growing seasons. It is possible that continuing this trial across multiple growing seasons, and combining long term fertility trials from the past could result in a more robust dataset that could provide more accurate results.

CHAPTER V

ASSESSMENT OF OSU RECOMMENDATIONS FOR POTASSIUM IN SOYBEANS

Introduction

Applied in the second most amount of macronutrients in the United States (USDA, 2018), Potassium (K) often provides mixed results in rate studies. Unlike nitrogen (N) as discussed in the previous chapter, K does not rely on yield based recommendations. Bray's Nutrient Mobility concept provides that K nutrient requirements, as an immobile nutrient in the soil, are based on sufficiency need (Bray, 1954). Using sufficiency models, current Oklahoma State University (OSU) soil test potassium recommendations are based on 100% sufficiency for soybeans at 137.5 ppm soil test K (STK) (Arnall, 2017).

Many studies have shown K fertilizer application increases yields under low STK (Casanova, 2000; Heckman & Kamprath, 1992; Jones et al., 1977), yet other studies have observed responses to K fertilizers at near-optimum or high levels of STK, and had locations with low STK not provide any responses (Mallarino, 2000; Reed, 2018). Additionally, while some work has been done evaluating K fertilizer timing in soybeans (Slaton et al., 2020), that was conducted in an irrigation setting, where incorporation of in-season fertilizer applications can happen in a timely fashion, whereas Oklahoma summers can be dry, and go weeks without rainfall.

Due to concern of in-season application of dry fertilizer not incorporating into the crop rooting zone, many producers look at options using foliar applications in order to alleviate any deficiencies seen in season. Mallarino et al. (2001) and Haq and Mallarino (2005) both investigated impact of foliar applied K on soybean yield and quality, and had mixed results, but concluded that foliar K is not a substitution for pre-plant fertilizer.

The objective of this study was to (1) assess OSU rate recommendations for potassium in soybeans, (2) assess viability for in-season application of dry and foliar K on dryland soybean. The author's hypothesis was that while site by site response variability will vary, on average, OSU recommendations for potassium will be adequate across varying environments and soil types. The authors also hypothesize that in-season application of K fertilizer, regardless of source, will not be a viable option for amelioration of yield.

Materials and Methods

Study Area

This trial was established at ten locations across the 2018, 2019, and 2020 growing seasons. The trial was a RCBD study, consisting of a 2 x 3 x 2 factorial plot design; 2 timings (pre-plant and side-dress in-season fertilizer application, at the R1 growth stage in soybeans) by 3 rates (½x, 1x, and 2x OSU K fertilizer recommended rate), with and without a foliar K application of K-Leaf (Ele-Max by Helena Agri-Enterprises, LLC), and a non-fertilized check. The product K-leaf has an analysis of 30% w/w of soluble potash (K_2O), derived from potassium hydroxide (KOH). One additional treatment included a split (½x rate pre-plant, ½x rate top-dress in-season, resulting in 1x rate for the season) fertilizer application. Rates were determined using the OSU recommendations based on a pre-plant soil test (0-15 cm), on a site-specific basis. Muriate of potash (0-0-60) was used as the fertilizer source of K. Top-dress fertilizer and foliar fertilizer application occurred at R1 reproductive stage. Foliar potassium fertilizer applied to manufacturer's recommendation, 11.7 L product ha^{-1}, applied using water as a carrier to a rate of 187.1 L ha^{-1}. Application was repeated after two weeks from first application, per manufacturer's recommendation. Plot size is 3.0 m x 6.1 m per treatment, with 3.0 m alleys between repetitions. Observations of deficiency symptoms were recorded throughout the growing season.

Soil Analyses

Composite pre-plant soil samples, consisting of at least fifteen 2.5 cm cores, were taken (0-15 cm) for background soil test information, results found in Table 9. Samples were dried at 65℃ overnight and ground to pass a 2 mm sieve prior to extraction and analysis, conducted following methods set by Crouse et al. (2014). The pH was measured by using a combination electrode within a 1:1 ratio of soil to water suspension. Nitrate-N was determined using a 1M KCl extraction solution with 2 g of soil to 20 mL of solution with 15 minutes of shaking time. Nitrate-N was then determined by automated colorimetric flow-injection analysis (Lachat Quickchem 8000, Loveland, CO). The Mehlich-3 (M-3) method was used to find extractable P, K, Ca, and Mg, by extracting 2 g of soil with 20 mL of M-3 solution and shaking for 5 minutes. Exchangeable S was found by mixing 10 g of soil with 25 mL of 0.008M calcium phosphate solution and shaking for 30 minutes. Concentration of P, K, Ca, Mg, and S in the extracts were determined with an inductively coupled plasma atomic emission spectrometer (ICP-AES).

Table 9 Soil Test analyses for each location. Values provided are pH, NO_3-N and SO_4-S (kg ha^{-1}), Soil test Phosphorus (STP), Soil Test Potassium (STK), Calcium and Magnesium (ppm), and Organic Matter (OM, %)

Year	Location	pH	NO_3-N	SO_4-S	STP	STK	Ca	Mg
			kg ha^{-1}			*mg kg^{-1}*		
2018	Bixby	-	-	-	-	100	-	-
	LCB 1	6.3	25	7	18	95	932	277
	Haskell 1	7.3	36	8	18	45	1776	56
2019	McCollough 1	7.2	6	4	35	75	1418	110
	LCB 2	5.6	30	-	17	95	715	209
	Haskell 2	6.9	3	-	18	45	-	-
2020	Haskell 3	5.7	4	9	57	40	723	109
	Ballagh	7.3	6	22	20	105	2595	290
	McCollough 2	6	30	13	8	45	1475	61
	McCollough 3	5.3	36	10	18	55	831	84

Weather data

Weather data was collected from Oklahoma's weather monitoring stations placed with at least one in every county, called Mesonet (McPherson et al., 2007). The closest Mesonet station to each location was used to monitor weather data <www.mesonet.org>. The Oklahoma Mesonet also publishes a report that has the average chance of precipitation for a given week at each station site, derived from historical data (Mesonet, 2018). Weekly probability rainfall chances were taken from this dataset for each location.

Grain Yield Sampling

At physiological maturity, plots were harvested utilizing Kincaid 8-XP plot combine (Kincaid Equipment Manufacturing; Haven, KS). Yield data was collected by the onboard Harvest Master Yield monitoring computer (Juniper Systems; Logan, UT), and grain samples were collected from each plot at harvest. To standardize yields, moisture content was adjusted to 13.3%.

Table 10 This table lists each location in this trial, with the year, soil type, pH, NO_3-N, soil test P, and soil test K.

Year	Location	Soil Type	Planting Date	R1 Application Date	STK	K Sufficiency
					ppm	*%*
2018	Bixby	Wynona Silty Clay Loam	5/23/2018	7/11/2018	100	89
2018	Haskell 1	Taloka Silt Loam	5/23/2018	7/11/2018	45	66
2018	LCB 1	Pulaski fine Sandy Loam	5/10/2018	7/02/2018	95	88
2019	Haskell 2	Taloka Silt Loam	5/17/2019	7/15/2019	45	66
2019	LCB 2	Taloka Silt Loam	5/15/2019	7/29/2019	95	88
2019	McCollough 1	Parsons Silt Loam	6/28/2019	8/13/2019	75	80
2020	Ballagh	Agra-Foraker Complex	6/26/2020	7/23/2020	105	91
2020	Haskell 3	Taloka Silt Loam	6/04/2020	7/23/2020	40	63
2020	McCollough 2	Bates Loam	6/06/2020	7/23/2020	45	66
2020	McCollough 3	Parsons Silt Loam	6/08/2020	7/23/2020	55	71

Statistical Analysis

Statistical analyses were conducted with treatment as fixed effect and block as random effect using PROC GLIMMIX (Tukey adjustment, alpha=0.05) of SAS Software, Version 9.4 (SAS Institute Inc., Cary, NC, USA). Figures were produced using package ggplot2 in R (R Core Team, 2020; Wickham, 2016).

Results and Discussion

Weather

All locations in 2018 recorded below average air temperature from mid-July through end of August (2° C below average annual temperature), but had slightly above average temperature from end of August through first of October (1.1° C above average annual temperature). All locations in 2018 also had below average rainfall from first of May through mid-July (1.6 mm below annual average for Haskell 1, 1.6 mm below annual average for Bixby, 1.9 mm below annual average for LCB 1). No location in 2018 experienced extended periods without significant rainfall events.

The air temperature in 2019 for all locations was below the long term average from end of May through first of August (1.1° C below average annual temperature), but had above average temperature from mid-August through first of October (2.0° above average annual temperature). All locations in 2019 also had above average rainfall from early May through end of June (3.6 mm above average annual rainfall for Haskell 2, 6.6 mm above average rainfall for McCollough 1, 7.9 mm above average annual rainfall for LCB 2). Above average rainfall in 2019 at McCollough 1 led to delayed planting till June 28, 2019. LCB 2 experienced an extended period of no rainfall from July 1-August 1.

All locations in 2020 also experienced below average air temperature from mid to late-May (1.8° C below average annual temperature), and very normal average temperature through all of June and July, followed by below average temperature from August through early-October (1.7° C below average annual temperature). All locations in 2020 had above average rainfall in May (3.8 mm above average rainfall for McCollough 2 and 3, 5.9 mm above average rainfall for Haskell 3, and 0.4 mm above average rainfall for Ballagh). This pushed back planting dates for McCollough 2 and 3 and Haskell 3 till the first week of June. Ballagh was not affected by rainfall, but was planted following wheat harvest. Haskell 3 experienced a period of very little rainfall from May 30 through June 23.

Potassium Response

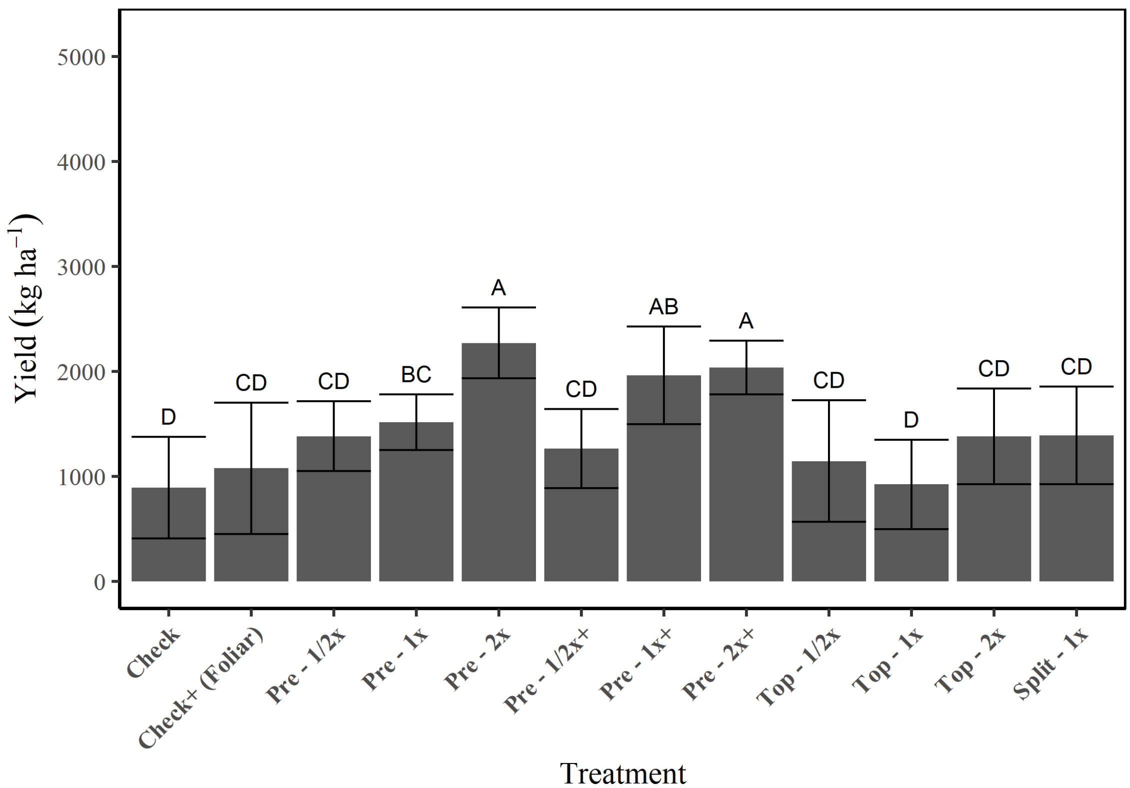
Based upon soil test potassium levels, fertilization was recommended for all locations, as each location was to some degree deficient in K. The STK of the locations ranged from 45 – 105 ppm, and sufficiency values ranged from 63 – 91% sufficient across locations (Table 10).

Analysis across all locations with block and location as random variables determined that treatment was not a significant effector yield, but had a trend (p=0.0694). Due to large variability between locations, including soil type, environment, yield, and response, each location was ran independently to discuss site-specific responses.

Across 10 locations, all locations displayed visual K deficiency early season, yet only two provided K responses to any treatment ($p \leq 0.0484$): Haskell 1 and Haskell 2. Both of these locations had yield significantly impacted by rate, but only Haskell 1 had timing as a significant effector. No location provided any significant grain yield response to the foliar application.

Haskell 1 in 2018 had pre-plant STK concentration of 45 ppm; with a resulting sufficiency of 66%. The STK fertilizer recommendation was 65 kg K ha^{-1}. Within seven days of planting there were two rainfall events, collectively totalling 21.8 mm of rainfall, which would have been adequate for nutrient incorporation. At side-dress application, there were two rainfall events within a week, collectively totalling 13.2 mm of rainfall, which also would have been adequate for nutrient incorporation. Treatment was found to be significant at this location ($p<0.0001$). Figure 26 displays treatment averages at this location, accompanied with statistical groupings (Tukey adjustment, alpha=0.05). The OSU recommended rate was found to have a significant effect over 0 K check. However, the treatment that provided the greatest increase over the check was the 2x rate, or 130 kg K ha^{-1}. Both rate and timing were found to be significant effectors for this location as well. For rate, 2x rate was found to be significantly different from the 0 K check, as well as the 0.5x rate. The 1x rate and the 2x rate were not found to be statistically different. For timing, pre-plant rate was found to be significant over both top-dress and the check application, but was not significantly different from the split application.

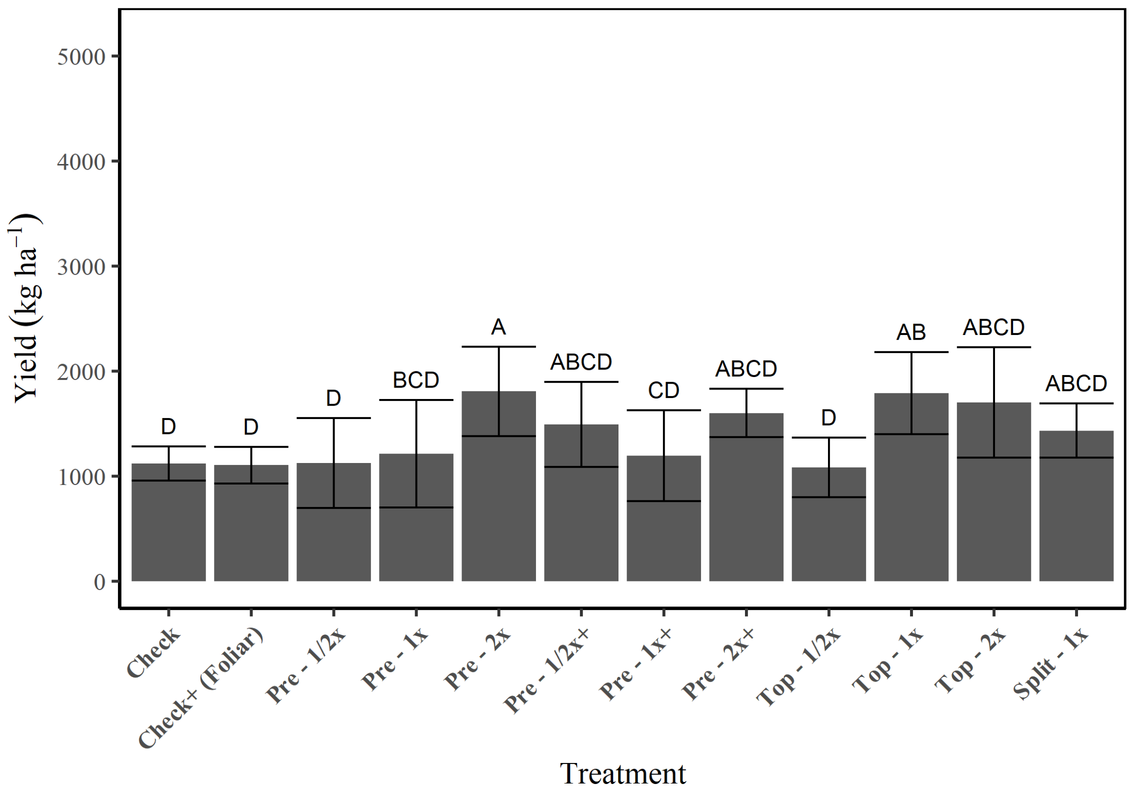
Figure 7 Grain yield and error bars from all treatments at Haskell 1 location. Soil test K at this location was 45 ppm, or 66% K Sufficient. Statistical significance denoted by letter coding, groups with similar letters are not different.



Haskell 2 in 2019 pre-plant STK concentration was 45 ppm, with a resulting K sufficiency of 66%. The K recommendations would have included an application of 65 kg K ha^{-1}. Within seven days of pre-plant fertilizer application, there were numerous rainfall events, collectively totalling 68 mm of rainfall, providing adequate moisture for nutrient incorporation. For the top-dress application, there was one rainfall event, totalling 11.9 mm of rainfall, providing adequate nutrient incorporation. Treatment was found to be significant at this location (p=0.0484). Figure 27 displays the treatment averages (kg ha^{-1}), accompanied with statistical grouping (Tukey adjustment, alpha=0.05). The OSU recommended treatment rate was not found to be significant different from the 0 K check. The treatment with the highest yield was found to be the pre-plant

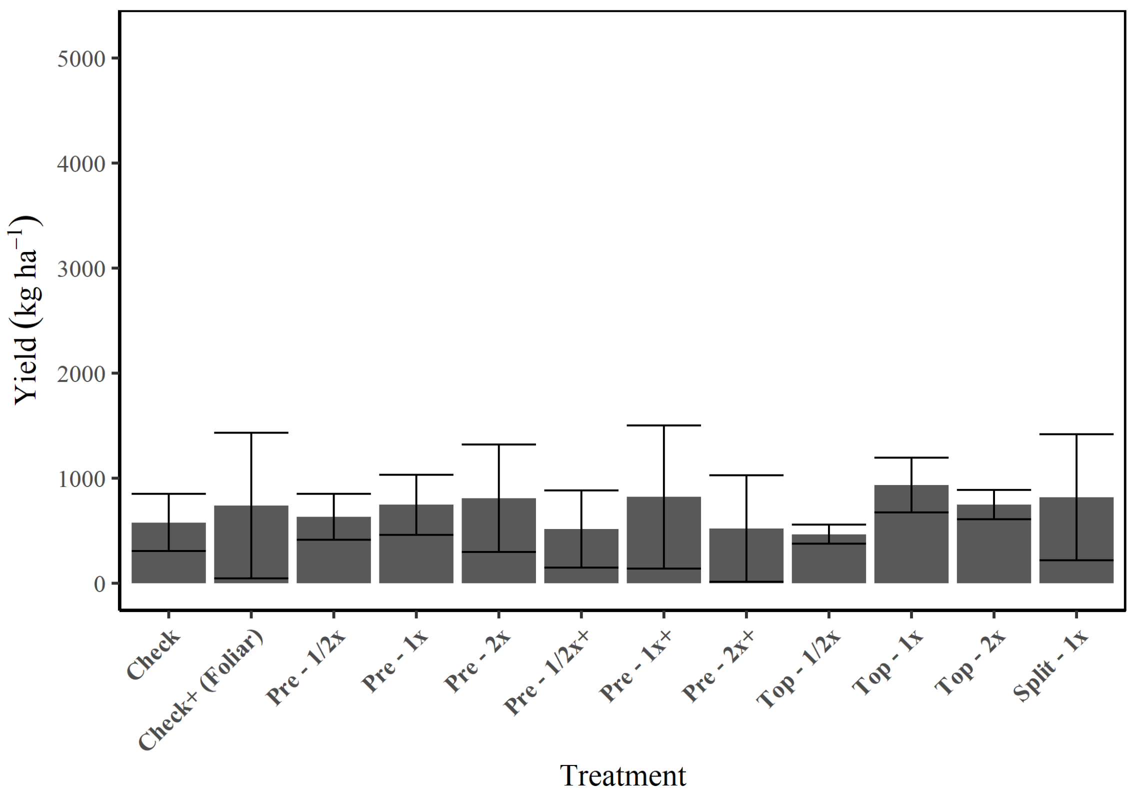
2x rate application. Rate was found to be significant for this location, similarly to Haskell 1, with 2x rate being significantly different from the 0 K check, as well as the 0.5 rate, but was not significant from 1x rate. Neither timing nor foliar was found to be significant effectors at this location.

Figure 8 Grain yield and error bars from all treatments at Haskell 2 location. Soil test K at this location was 45 ppm, or 66% K Sufficient. Statistical significance denoted by letter coding, groups with similar letters are not different.



Haskell 3 in 2020 had pre-plant STK concentrations of 40 ppm, the lowest of all tested locations, with a resulting K sufficency of 63%. The soil test K fertilzier recommendation was 65 kg K ha^{-1}. Within 8 days of pre-plant fertilizer application, there was only one rainfall event, totalling 0.25 mm of rainfall. Nineteen days would pass before receiving significant rainfall event, totalling 24.4 mm of rainfall. For the top-dress fertilizer application, within 24 hours, this location received 15.2 mm of rainfall, providing adequate moisture for nutrient incorporation. This location had very poor stand, in part due to high moisture at planting, leading to emergence issues, proceeded by little to no moisture for the next 19 days. Stand, and therefore, yield, was highly variable across the trial, leading to very low average yields at this location, averaging 695 kg ha^{-1}. Figure 28 displays the average yield for each treatment, as well as error bars depicting the range of yields for that treatment.

Figure 9 Grain yield and error bars from all treatments at Haskell 3 location. Soil test K at this location was 40 ppm, or 63% K Sufficient.

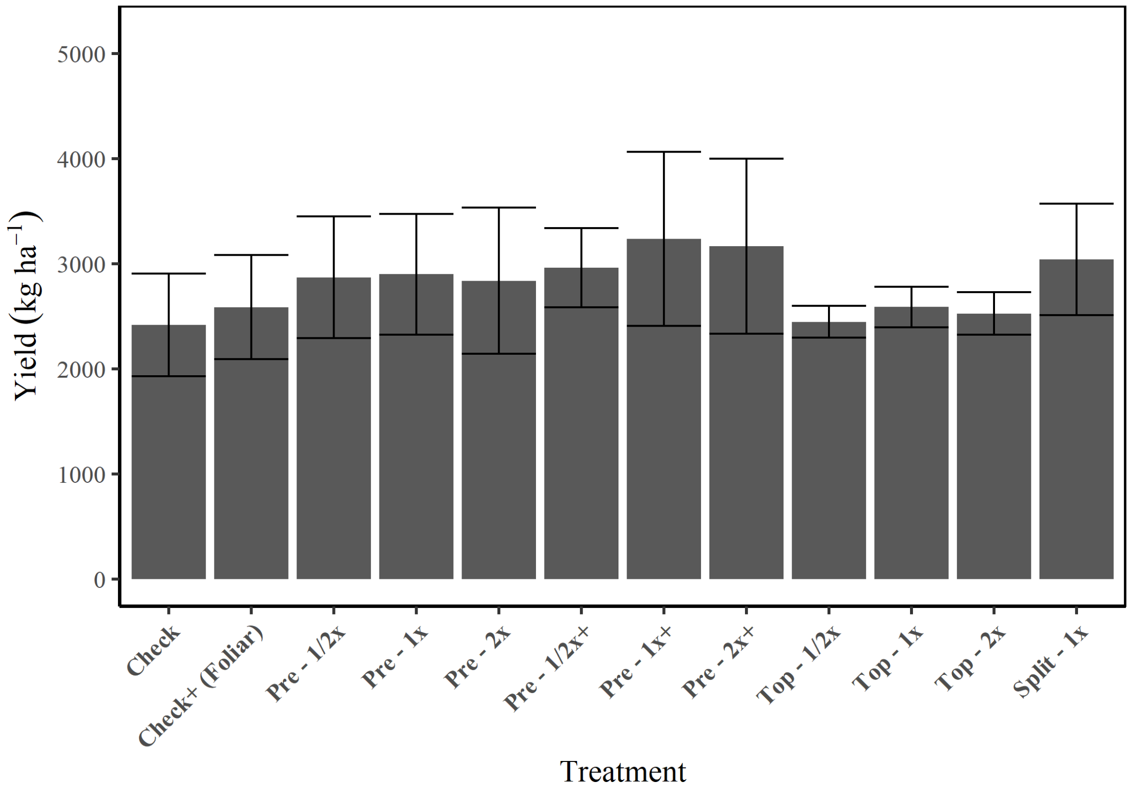


All three Haskell locations (Haskell 1, 2, and 3) were planted on the same research farm (Eastern Research Station, Haskell, OK), and were within 600 m of each other. This location is known for its low STK concentrations found in the soil, and was ideal for this project. For both responsive locations (Haskell 1 and 2), the pre-plant 2x rate application maximized yield. Though not statistically significant, the top-dress 1x rate maximized yield for Haskell 3.

Haskell 1 and 2 had adequate rainfall within 7 days of planting and pre-plant applications, and therefore, had incorporation of nutrients from the fertilizer. Haskell 3 did not have significant rainfall for 19 days, and therefore, the pre-plant fertilizer took some time before becoming available for plant uptake. The probability of rainfall during the week of planting and pre-plant fertilizer applications for Haskell 1 and 2 were 13.6% and 12.1%, respectively. Haskell 3, planted two weeks later than the other years, had rain probability drop to 8.0%, and could take up to two weeks for that probability to increase to 17.1%. Had their been adequate rainfall directly after planting and pre-plant fertilizer application, this location may have had a positive response to K applications. Top-dress application weeks at all three locations had at most 8.0% probability of rainfall of at least 13 mm, and would not get above that value for over 3 weeks, providing more of a risk for applications during mid July.

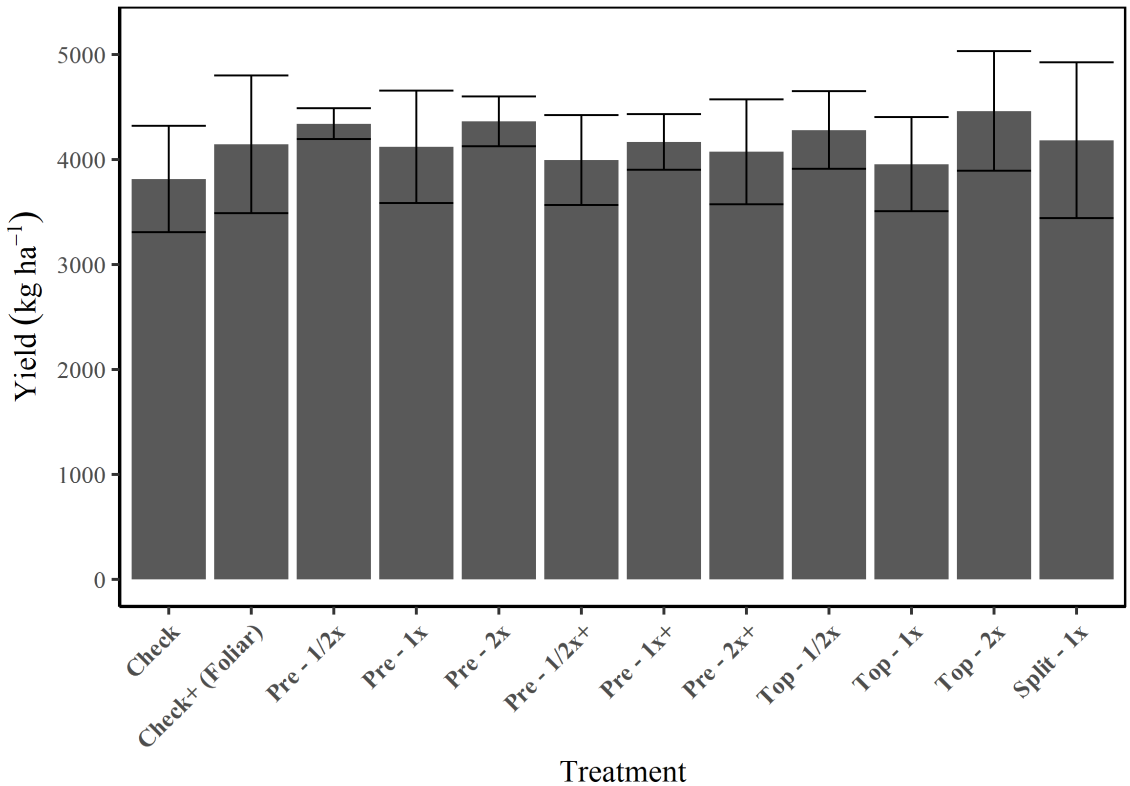
Bixby in 2018 had pre-plant STK concentration of 100 ppm, resulting in a K sufficiency of 89%. The fertilizer K recommendation was 28 kg K ha^{-1}. Within 7 days of planting and pre-plant fertilization, there was cumulative rainfall of 28.7 mm of rain, allowing adequate nutrient incorporation. Within 7 days of top-dress application, there was cumulative rainfall of 24.6 mm. Figure 29 displays the average yield for each treatment, as well as error bars depicting the range of yields for that treatment.

Figure 10 Grain yield and error bars from all treatments at Bixby location. Soil test K at this location was 100 ppm, or 89% K Sufficient.



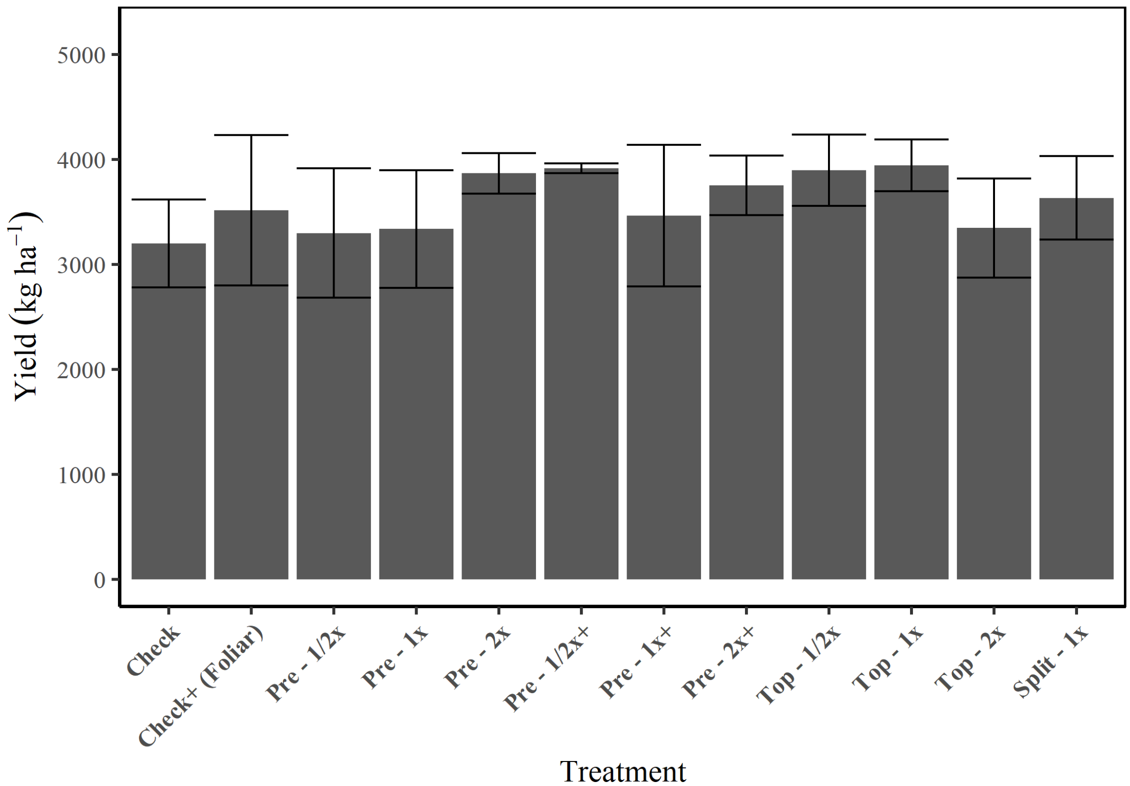
LCB 1 (Figure 30) in 2018 had pre-plant STK concentrations of 95 ppm, with a resulting K sufficiency of 88%. The STK fertilizer recommendation was 28 kg K ha^{-1}. Within seven days of planting, the cumulative rainfall totals amounted to 2.0 mm of rainfall; jumping to 11.9 mm within 14 days. There were no rainfall events within seven days of top-dress applications, but within 14 days, there were 11.2 mm of rain accumulated on this location.

Figure 11 Grain yield and error bars from all treatments at LCB 1 location. Soil test K at this location was 95 ppm, or 88% K Sufficient.



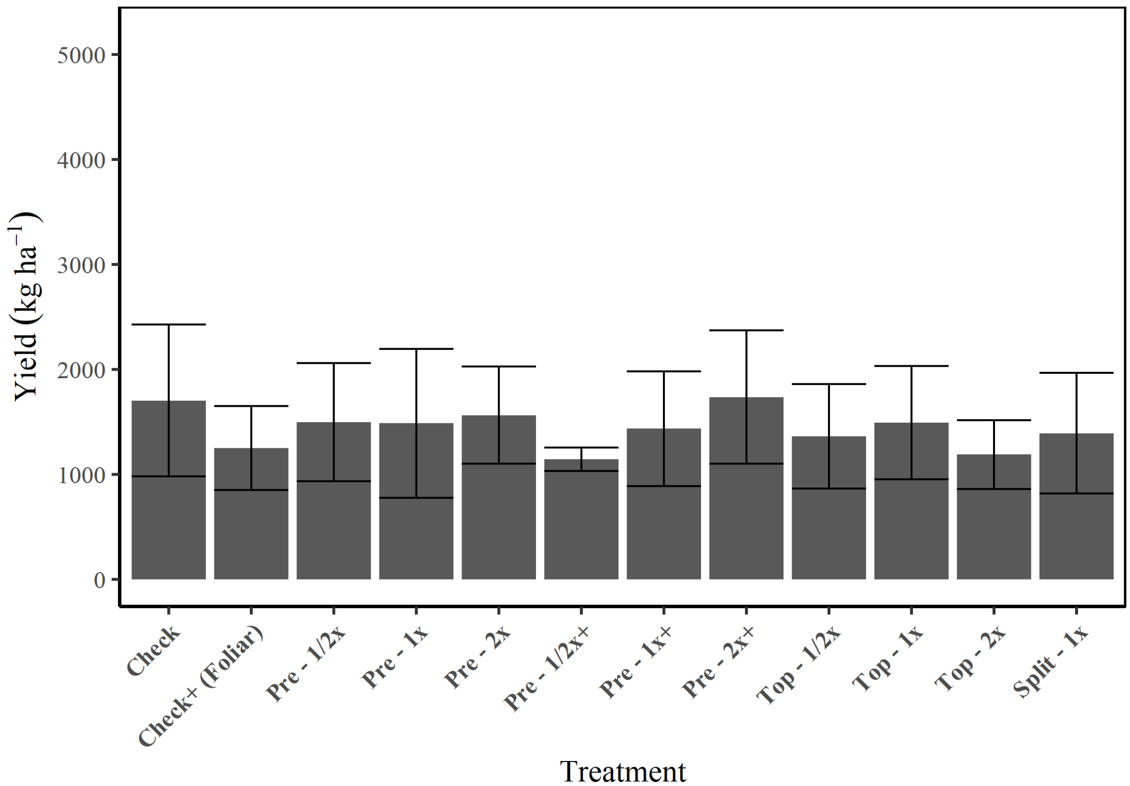
LCB 2 (Figure 32) in 2019 had pre-plant STK concentration of 95 ppm, with a resulting K sufficiency of 88%. The STK fertilizer recommendation was 28 kg K ha^{-1}. Within seven days, this location had heavy rainfall, accumulating to 184 mm of rainfall, leading to poor stand of this location. Two blocks of this trial were replanted, and still did not recover fully. Within seven days of top-dress fertilizer application, this location accumulated 24.6 mm of rainfall, adequate for good nutrient incorporation. While K is not mobile within the soil, the high rainfall amounts occurring directly after planting and pre-plant fertilizer applications could have led to runoff in this area, moving that fertilizer away from the plots. Stand issues provided high variability within and across all treatments, and therefore, not much can be taken from this location.

Figure 12 Grain yield and error bars from all treatments at LCB 2 location. Soil test K at this location was 95 ppm, or 88% K Sufficient.



Ballagh in 2020 had pre-plant STK concentrations of 105 ppm, the highest concentration across all locations, resulting in a K sufficiency of 91%. The STK fertiilzer recommendation for this location was 28 kg K ha^{-1}. This location was planted following a winter wheat harvested crop, so was planted very late into the season. Within seven days of planting, the cumulative rainfall total was 17.3 mm of rain. For top-dress application, there was an accumulation of 100.6 mm of rain within seven days.

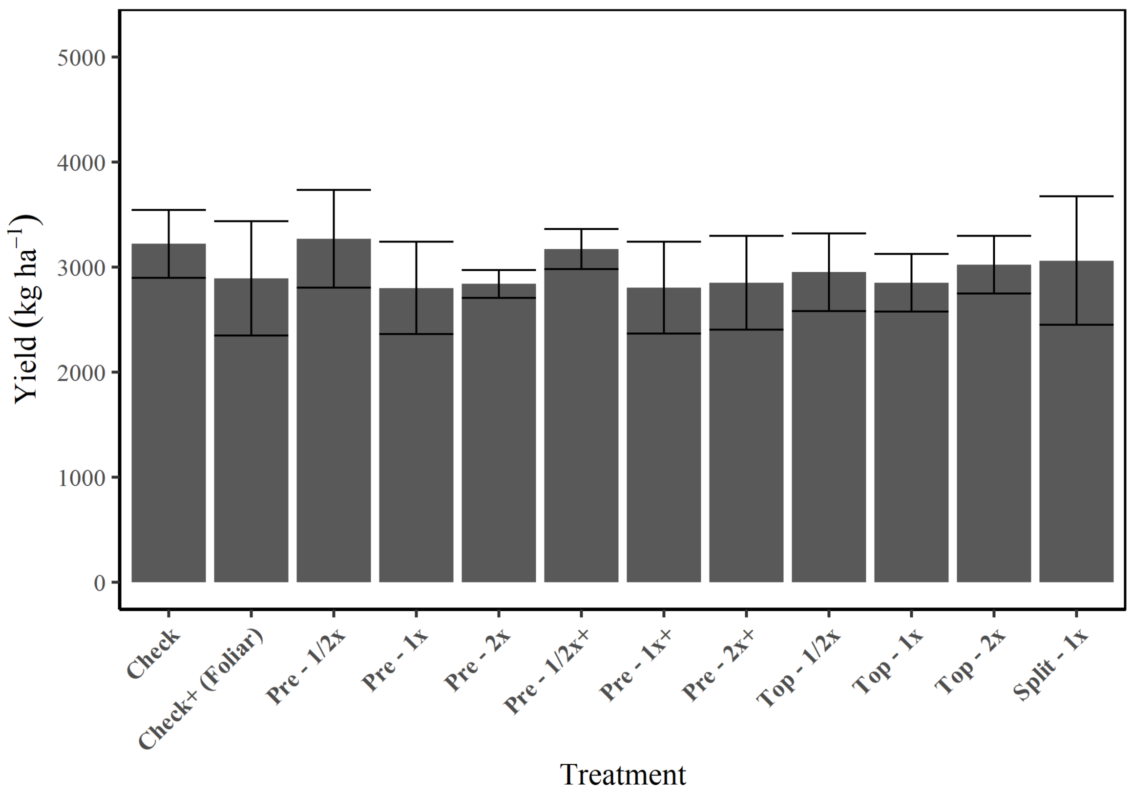
Figure 13 Grain yield and error bars from all treatments at Ballagh location. Soil test K at this location was 105 ppm, or 91% K Sufficient.



For Bixby, LCB 1, LCB 2, and Ballagh, these locations only had marginally K deficient soils. Previous work has shown mixed results from locations that have marginally deficient soils, and most responses were attributed to importance of K in drought-stress conditions (Mallarino, 2000; Reed, 2018). Across all these locations, drought-stress conditions were not found, and could explain why there was no K response to any additional K fertilizer.

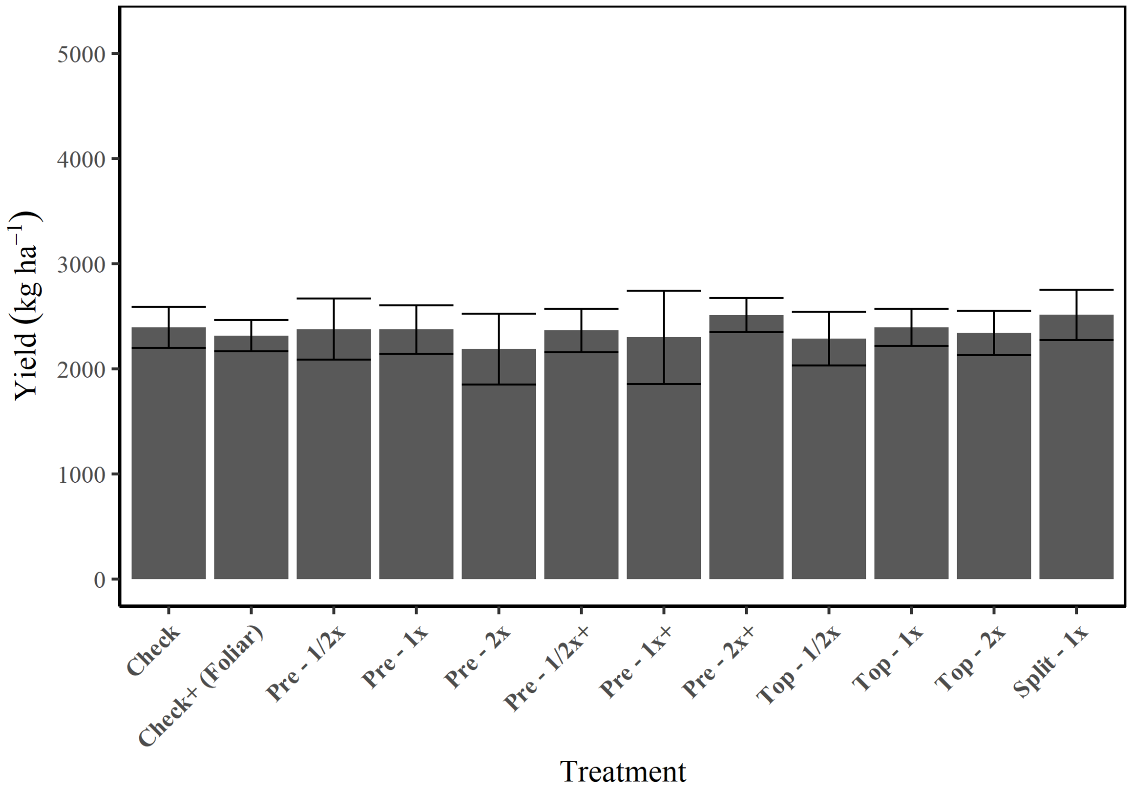
McCollough 1 in 2019 had pre-plant STK concentration of 75 ppm, resulting in K suffiency of80%. The STK fertilizer recommendations would include an application of 47 kg K ha^{-1}. This location had lots of rainfall from May through June, and was delayed planting till June 28. Within seven days of planting, this location received 12.4 mm of rainfall, enough for adequate incorporation. For top-dress fertilizer application, this location received 7.4 mm of rainfall within seven days as well.

Figure 14 Grain yield and error bars from all treatments at McCollough 1 location. Soil test K at this location was 75 ppm, or 80% K Sufficient.



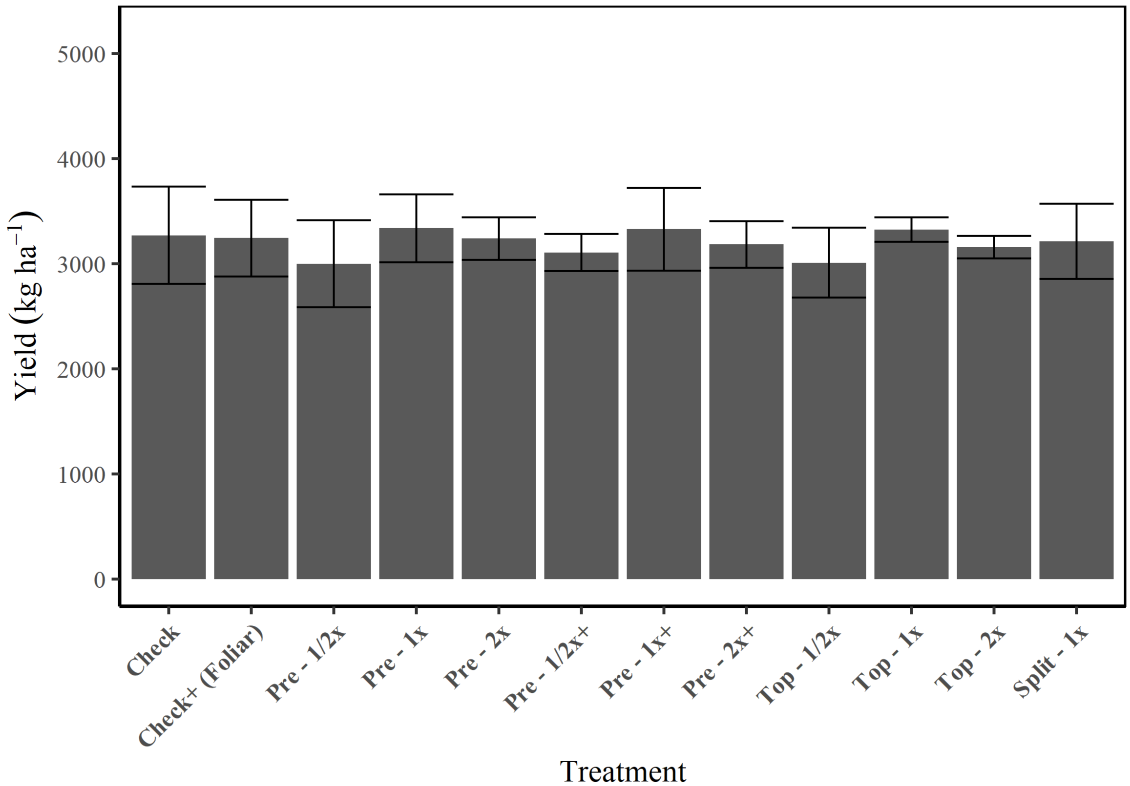
McCollough 2 (Figure 33) in 2020 had pre-plant STK concentration of 45 ppm, resulting in a K sufficiency of 66%. The STK fertilizer recommendation for this location was 65 kg K ha^{-1}. There were no rainfall events within seven days of planting or pre-plant fertilizer applications; at 13 days, this location received 9.9 mm of rainfall. Within seven days of top-dress fertilizer application, this location received 148.6 mm of rainfall. Due to field conditions after high rainfall accumulation, this location did not receive a second foliar application of foliar K.

Figure 15 Grain yield and error bars from all treatments at McCollough 2 location. Soil test K at this location was 45 ppm, or 66% K Sufficient.



McCollough 3 (Figure 34) in 2020 was within 5 km of McCollough 2, and had pre-plant STK concentration of 55 ppm, resulting in a K sufficiency of 71%. The STK fertilizer recommendation for this location was 56 kg K ha^{-1}. This location would not receive any rainfall until 15 days after planting or pre-plant fertilizer application, when it received 9.9 mm of rainfall. Within seven days of top-dress fertilizer application, this location received 148.6 mm of rainfall. Due to field conditions after the rainfall, this location also did not receive a second foliar application of foliar K.

Figure 16 Grain yield and error bars from all treatments at McCollough 3 location. Soil test K at this location was 55 ppm, or 71% K Sufficient.



All McCollough 1, 2, and 3 locations were located within 5 km of each other, and each managed by the same producer. This producer planted these locations later into the growing season due to lots of rainfall in May in both years. Potassium deficiencies were noted at these locations very early within the season across the low/0 K treatments, but disappeared by reproductive stages. This tells the authors that the higher rates of K were allowing the crop to not show any deficiences. This also displays, however, that since the 0 K checks were also not showing any K deficiencies at R1, the plant was finding the required K for reproduction. Studies have shown that soil K levels fluctuate throughout the season, and are mainly affected by plant growth, and therefore, seasonal fluctuations could be attributed to disappearing deficiencies. (Keeney et al., 2020; Roberts, 1987). There is also a chance that deficiencies were found at this location early in the season, until root growth reached a depth that had adequate K concentrations, as authors did not sample below 15 cm depth across this trial.

For the two locations (Haskell 1 and 2) that were found to respond to any treatment, top-dress applications provided mixed results. Haskell 1 top-dress application was not different than the 0 K check, but for Haskell 2, 1x and 2x top-dress rates, while still not statistically different from the chcek, were within 100 kg ha^{-1} of the highest yielding treatment, pre-plant 2x. Split 1x application follows the same pattern at both these locations as well. Both of these locations have the same soil type, very similar soil test analysis, and had very similar growing seasons, so no cause for differences between locations can be found from those characteristics of the season. Haskell 2 had lower yields as compared to Haskell 1, and could be a source of difference to the lack of differentiation of treatments. Rainfall probability data provided insight into better timings for applying dry fertilizers for incorporation, and Haskell 1 and 2 (locations with positive responses) were planted and topdressed within the highest probability of rainfall chances during their respective stages in growth. While Haskell 3 was planted during a time of lower rainfall probability (which was evident in that year), variability in stand and yields do not allow for any assessments of application timing. For the rest of the locations, the lack of any K response complicates any assessment of the use of top-dress/split application in soybeans.

No location resulted in a statistical yield response to any foliar fertilizer application. The product has an analysis of 30% w/w of soluble potash (K_2O), derived from potassium hydroxide, and is a very basic solution (SDS: 8.5-10.0). After the first application, within 24 hours, there was visual damage to the leaf where the product was applied. The product rates and carrier rates were those suggested on the label by the manufacturer, and this can be contributed to its alkalinity. Within a week, all signs of visual damage had gone away, and no statistical negative response to the application. Only one location did not show any visual damage post-application, and that was the

Bixby location. This location, situated in the eastern portion of the state, is in an area that has higher humidity than all the other locations. This could have attributed to the lack of damage. Even though not statistically significant, treatments receiving foliar K application had higher yields at Haskell 1 (+70 kg ha^{-1}), Haskell 2 (+33 kg ha^{-1}), and Bixby (+250 kg ha^{-1}) than treatments that did not. Oklahoma is known for having very dry summers, leading to low humidity, especially in the central- and western- portions of the state. Though there is not enough data to determine the accuracy, this could show that any response to foliar potassium could be dependent on higher humidity.

Conclusion

The experimental design of this project was not constructed to determine the optimum K rate for each location, but to provide insight into whether the current recommendations were accurate, or required more or less than recommended, for a range of K deficiencies. Across 10 locations, all were below the critical threshold of 137.5 ppm of potassium, ranging from 40-105 K ppm, or 63-91% K sufficient. Only 2 locations provided a statistically significant positive response to the addition of K fertilizer, both of which had sub-70% K sufficiency values. Of these two locations, both had highest statistical yields at the pre-plant 2x rate. This indicated that current OSU recommendations for these locations would not have provided the application needed to maximize yield. For the other 8 locations, due to high variability, marginal K deficiency, and crop recovery, no statistically significant K response was found. The authors hypothesized that OSU recommendations for potassium would be adequate in varying environments and soil types, and results did not provide evidence that this was true.

Only one location, Haskell 1, was yield significantly impacted by timing, while the other responsive location, Haskell 2, was not significantly impacted by timing. This provides evidence that in-season side dress applications could be a viable option for recovering yield from deficiency symptoms in certain situations, contrary to authors hypothesis.

This work displayed that responses to K were not always correlated with low STK, even when deficiency symptoms are seen in season, similar to previous work done in Oklahoma on soybeans (Reed, 2018). Due to both of the author's hypotheses failing, the authors suggest that a timing/rate study should be conducted on similar locations and sufficiencies in order to determine optimum rates and viability of in-season applications.

REFERENCES

Abedi, T., Alemzadeh, A., & Kazemeini, S. A. (2011). Wheat yield and grain protein response to nitrogen amount and timing. *Australian Journal of Crop Science*, *5*(3), 330.

Alcoz, M. M., Hons, F. M., & Haby, V. A. (1993). Nitrogen fertilization timing effect on wheat production, nitrogen uptake efficiency, and residual soil nitrogen. *Agronomy Journal*, *85*(6), 1198-1203.

Andersen, M. N. C. R. J. R. L. (2009). The interaction effects of potassium and drought in field-grown barley. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science*.

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

Ashley, M. K., Grant, M., & Grabov, A. (2006). Plant responses to potassium deficiencies: a role for potassium transport proteins. *J Exp Bot*, *57*(2), 425-436. https://doi.org/10.1093/jxb/erj034

Barton, C. (2002). Clay minerals. *In: Rattan Lal, comp., ed. Encyclopedia of Soil Science. New York, New York: Marcel Dekker: 187-192.*

Brady, N. C. (1984). *The Nature and Properties of Soils, Ninth Edition* (9th ed.). Macmillan Publishing Company.

Bray, R. H. (1954). A Nutrient Mobility Concept of Soil-Plant Relationships. *Soil Science*, *78*(1), 9-22. https://journals.lww.com/soilsci/Fulltext/1954/07000/A_NUTRIENT_MOBILITY_CONCEPT_OF_SOIL_PLANT.2.aspx

Casanova, E. (2000). Phosphorus and potassium fertilization and mineral nutrition of soybean. *Interciencia*, *25*(2), 92-95.

Crouse, K. K., Hardy, D. H., Heckendorn, S., Huluka, G., D.K.Joines, Kissel, D. E., Miller, R., Mitchell, C. C., Moore, K. P., Mylavarapu, R., Oldham, J. L., Provin, T., Savoy, H. J., Sikora, F. J., Sonon, L., Wang, J. J., Warncke, D. D., & Zhang, H. (2014). *Soil Test Methods From the Southeastern United States* (F. J. S. K. P. Moore;, Ed.).

Dhillon, J. S., Eickhoff, E. M., Mullen, R. W., & Raun, W. R. (2019). World Potassium Use Efficiency in Cereal Crops. *Agronomy Journal*, *111*(2), 889-896. https://doi.org/10.2134/agronj2018.07.0462

Eichert, T., Goldbach, H. E., & Burkhardt, J. (1998). Evidence for the Uptake of Large Anions through Stomatal Pores. *Botanica Acta*, *111*(6), 461-466. https://doi.org/10.1111/j.1438-8677.1998.tb00733.x

Fernández, V., & Brown, P. H. (2013). From plant surface to plant metabolism: the uncertain fate of foliar-applied nutrients. *Frontiers in plant science*, *4*, 289-289. https://doi.org/10.3389/fpls.2013.00289

Filella, I., Serrano, L., Serra, J., & Peñuelas, J. (1995). Evaluating Wheat Nitrogen Status with Canopy Reflectance Indices and Discriminant Analysis. *Crop Science*, *35*(5),

cropsci1995.0011183X003500050023x. https://doi.org/10.2135/cropsci1995.0011183X003500050023x
Girma, K., Holtz, S., Tubaña, B., Solie, J., & Raun, W. (2010). NITROGEN ACCUMULATION IN SHOOTS AS A FUNCTION OF GROWTH STAGE OF CORN AND WINTER WHEAT. *Journal of Plant Nutrition*, *34*(2), 165-182. https://doi.org/10.1080/01904167.2011.533320
Goli-Kalanpa, E., Roozitalab, M. H., & Malakouti, M. J. (2008). Potassium Availability as Related to Clay Mineralogy and Rates of Potassium Application. *Communications in Soil Science and Plant Analysis*, *39*(17-18), 2721-2733. https://doi.org/10.1080/00103620802358870
Gu, C., & Riley, W. J. (2010). Combined effects of short term rainfall patterns and soil texture on soil nitrogen cycling — A modeling analysis. *Journal of Contaminant Hydrology*, *112*(1), 141-154. https://doi.org/https://doi.org/10.1016/j.jconhyd.2009.12.003
Haq, M. U., & Mallarino, A. P. (2005). Response of Soybean Grain Oil and Protein Concentrations to Foliar and Soil Fertilization. *Agronomy Journal*, *97*(3), 910-918. https://doi.org/10.2134/agronj2004.0215
Heckman, J., & Kamprath, E. (1992). Potassium accumulation and corn yield related to potassium fertilizer rate and placement. *Soil Science Society of America Journal*, *56*(1), 141-148.
Holford, I., Doyle, A., & Leckie, C. (1992). Nitrogen response characteristics of wheat protein in relation to yield responses and their interactions with phosphorus. *Australian Journal of Agricultural Research*, *43*(5), 969-986. https://doi.org/https://doi.org/10.1071/AR9920969
Jiménez, M. P., Effrón, D., de la Horra, A. M., & Defrieri, R. (1996). Foliar potassium, calcium, magnesium, zinc, and manganese content in soybean cultivars at different stages of development. *Journal of Plant Nutrition*, *19*(6), 807-816. https://doi.org/10.1080/01904169609365163
Johnston, A. M., & Bruulsema, T. W. (2014). 4R Nutrient Stewardship for Improved Nutrient Use Efficiency. *Procedia Engineering*, *83*, 365-370. https://doi.org/https://doi.org/10.1016/j.proeng.2014.09.029
Jones, G., Lutz, J., & Smith, T. (1977). Effects of Phosphorus and Potassium on Soybean Nodules and Seed Yield 1. *Agronomy Journal*, *69*(6), 1003-1006.
Keeney, A. B., Ritchey, E. L., & Bailey, W. A. (2020). Soil test potassium changes over time following fall potassium application in three western Kentucky soils. *Agrosystems, Geosciences & Environment*, *3*(1), e20058. https://doi.org/10.1002/agg2.20058
Kincheloe, S. (1994). Tools to aid management: the use of site specific management [Article]. *Journal of Soil and Water Conservation*, *49*, S43+.
Mallarino, A. P., Haq, M. U., Wittry, D., & Bermudez, M. (2001). Variation in Soybean Response to Early Season Foliar Fertilization among and within Fields Iowa Agric. Home Econ. Exp. Stn. Journal Paper no. J-18809. Project 3233. *Agronomy Journal*, *93*(6), 1220-1226. https://doi.org/10.2134/agronj2001.1220
Mallarino, A. P. R. B. D. W. (2000). Corn and Soybean Response to Potassium Fertilization and Placement [Encyclopedia Article]. *ICM News Archive*, *IC-484*(22), 166-168.
McPherson, R. A., Fiebrich, C. A., Crawford, K. C., Kilby, J. R., Grimsley, D. L., Martinez, J. E., Basara, J. B., Illston, B. G., Morris, D. A., Kloesel, K. A., Melvin, A. D., Shrivastava, H., Wolfinbarger, J. M., Bostic, J. P., Demko, D. B., Elliott, R. L., Stadler, S. J., Carlson, J. D., & Sutherland, A. J. (2007). Statewide Monitoring of the Mesoscale Environment: A Technical Update on the Oklahoma Mesonet. *Journal of Atmospheric and Oceanic Technology*, *24*(3), 301-321. https://doi.org/10.1175/jtech1976.1

Melaj, M., Echeverría, H., López, S., Studdert, G., Andrade, F., & Bárbaro, N. (2003). Timing of Nitrogen Fertilization in Wheat under Conventional and No-Tillage System. *Agronomy Journal - AGRON J*, *95*. https://doi.org/10.2134/agronj2003.1525

Mesonet. (2018). *Rain Probability Tables*.

Mullen, R., Freeman, K., Raun, W., Johnson, G., Stone, M., & Solie, J. (2003). Identifying an In-Season Response Index and the Potential to Increase Wheat Yield with Nitrogen. *Agronomy Journal - AGRON J*, *95*. https://doi.org/10.2134/agronj2003.0347

Nearing, M. A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Le Bissonnais, Y., Nichols, M. H., Nunes, J. P., Renschler, C. S., Souchère, V., & van Oost, K. (2005). Modeling response of soil erosion and runoff to changes in precipitation and cover. *CATENA*, *61*(2), 131-154. https://doi.org/https://doi.org/10.1016/j.catena.2005.03.007

Nelson, K. A., Motavalli, P. P., Stevens, W. E., Dunn, D., & Meinhardt, C. G. (2010). Soybean Response to Preplant and Foliar-Applied Potassium Chloride with Strobilurin Fungicides. *Agronomy Journal*, *102*(6), 1657-1663. https://doi.org/10.2134/agronj2010.0065

Omara, P., Aula, L., Oyebiyi, F., & Raun, W. R. (2019). World cereal nitrogen use efficiency trends: Review and current knowledge. *Agrosystems, Geosciences & Environment*, *2*(1), 1-8.

Porter, J. R., & Gawith, M. (1999). Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy*, *10*(1), 23-36. https://doi.org/https://doi.org/10.1016/S1161-0301(98)00047-1

Quinn, R. (2021). *DTN Retail Fertilizer Trends*. DTN. Retrieved Feb 25 from

R Core Team. (2020). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Raun, W., Figueiredo, B., Dhillon, J., Fornah, A., Bushong, J., Zhang, H., & Taylor, R. (2017). Can yield goals be predicted? *Agronomy Journal*, *109*(5), 2389-2395.

Raun, W., Solie, J., Johnson, G., Stone, M., Lukina, E., Thomason, W., & Schepers, J. s. (2001). In-Season Prediction of Potential Grain Yield in Winter Wheat Using Canopy Reflectance. *Agron. J.*, *93*. https://doi.org/10.2134/agronj2001.931131x

Raun, W. R. (2018). *Library of Yield Prediction Equations*. Oklahoma State University. Retrieved March 22, 2021 from http://nue.okstate.edu/Yield_Potential.htms

Raun, W. R., & Johnson, G. V. (1999). Improving Nitrogen Use Efficiency for Cereal Production. *Agronomy Journal*, *91*(3), 357-363. https://doi.org/10.2134/agronj1999.00021962009100030001x

Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L., Mullen, R. W., Freeman, K. W., Thomason, W. E., & Lukina, E. V. (2002). Improving Nitrogen Use Efficiency in Cereal Grain Production with Optical Sensing and Variable Rate Application Contribution from the Oklahoma Agric. Exp. Stn. *Agronomy Journal*, *94*(4), 815-820. https://doi.org/10.2134/agronj2002.8150

Raun, W. R., Solie, J. B., Stone, M. L., Martin, K. L., Freeman, K. W., Mullen, R. W., Zhang, H., Schepers, J. S., & Johnson, G. V. (2005). Optical Sensor-Based Algorithm for Crop Nitrogen Fertilization. *Communications in Soil Science and Plant Analysis*, *36*(19-20), 2759-2781. https://doi.org/10.1080/00103620500303988

Reed, V. (2018). *On-Farm Evaluation of Double Crop Fertility Management in Oklahoma* Oklahoma State University]. OSU Theses.

Roberts, A. H. C. (1987). Seasonal variation in soil tests and nutrient content of pasture at two sites in Taranaki. *New Zealand Journal of Experimental Agriculture*, *15*(3), 283-294. https://doi.org/10.1080/03015521.1987.10425573

Sembiring, H., Lees, H. L., Raun, W. R., Johnson, G. V., Solie, J. B., Stone, M. L., DeLeon, M. J., Lukina, E. V., Cossey, D. A., LaRuffa, J. M., Woolfolk, C. W., Phillips, S. B., & Thomason, W. E. (2000). Effect of growth stage and variety on spectral radiance in

winter wheat. *Journal of Plant Nutrition*, *23*(1), 141-149. https://doi.org/10.1080/01904160009382003
Slaton, N. A., Roberts, T. L., Ross, W. J., & Richmond, T. L. (2020). Irrigated soybean response to granular fertilizer potassium application timing. *Agronomy Journal*, *112*(5), 4344-4357. https://doi.org/https://doi.org/10.1002/agj2.20342
Souza, J. L. B. (2018). *Impact of Nitrogen Fertilizer Application Timing on Winter Wheat* Oklahoma State University]. OSU Theses. https://hdl.handle.net/11244/317705
USDA-NASS. (2020). *Oklahoma Agricultural Statistics 2020* (Oklahoma Agricultural Statistics, Issue.
USDA, E. R. S. (2018). *Fertilizer Use and Price*. USDA ERS
Wang, M., Zheng, Q., Shen, Q., & Guo, S. (2013). The critical role of potassium in plant stress response. *Int J Mol Sci*, *14*(4), 7370-7390. https://doi.org/10.3390/ijms14047370
Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org

APPENDICES

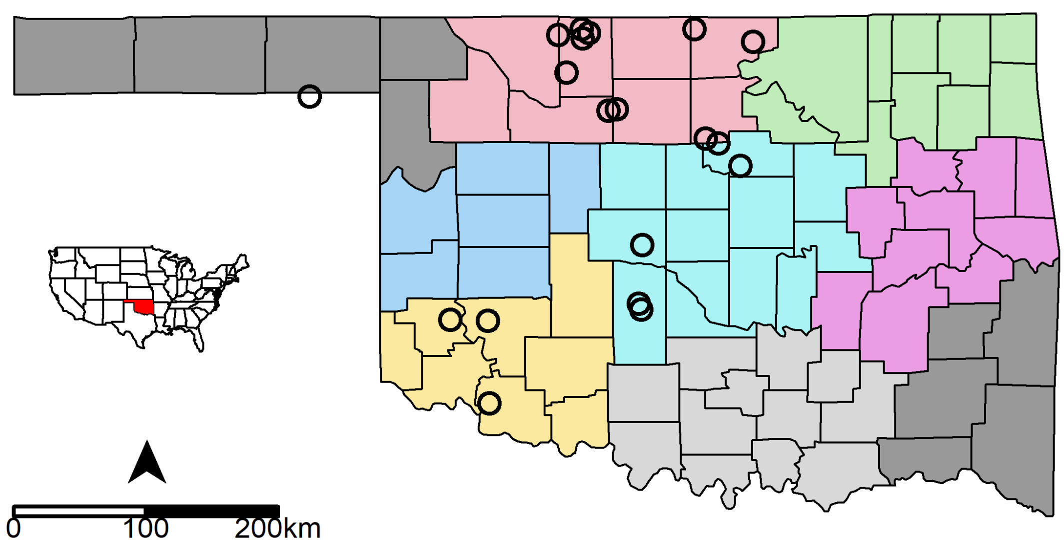


Figure 17 Map of all N rate and timing trials across Oklahoma for Chapter 3 and Chapter 4. Color regions represent different climatological zones.

Figure 18 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Byron 1 location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

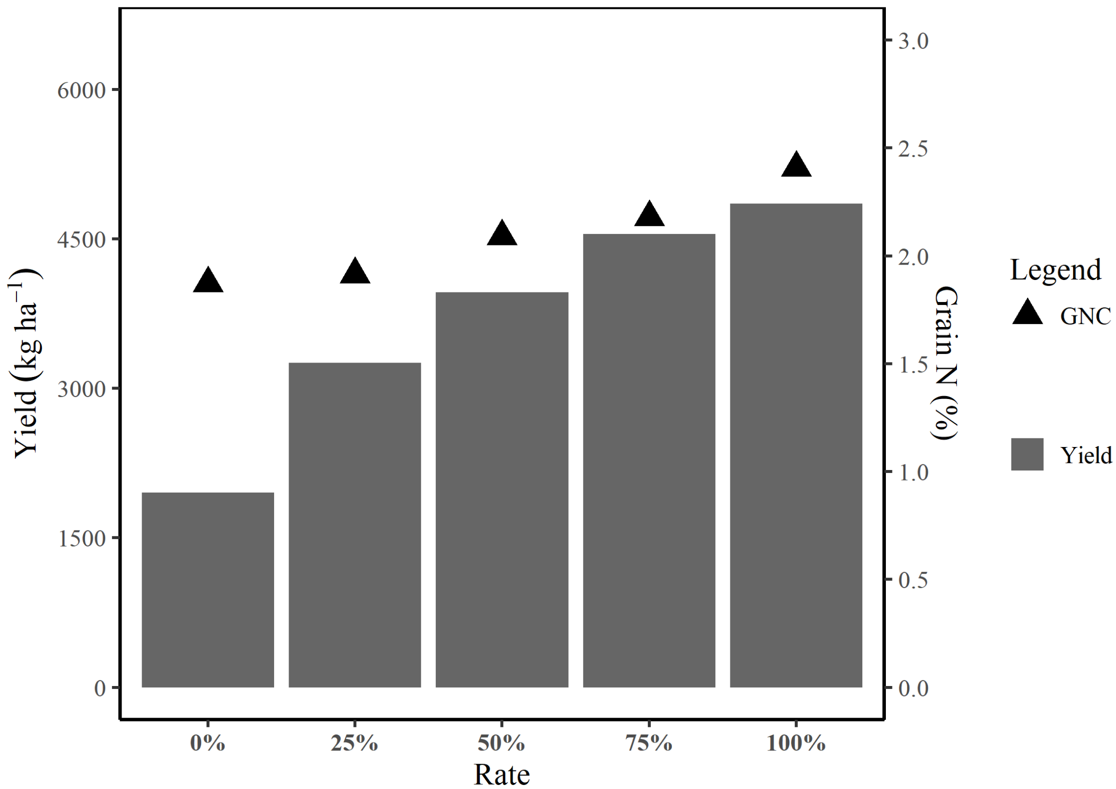


Figure 19 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Capron location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

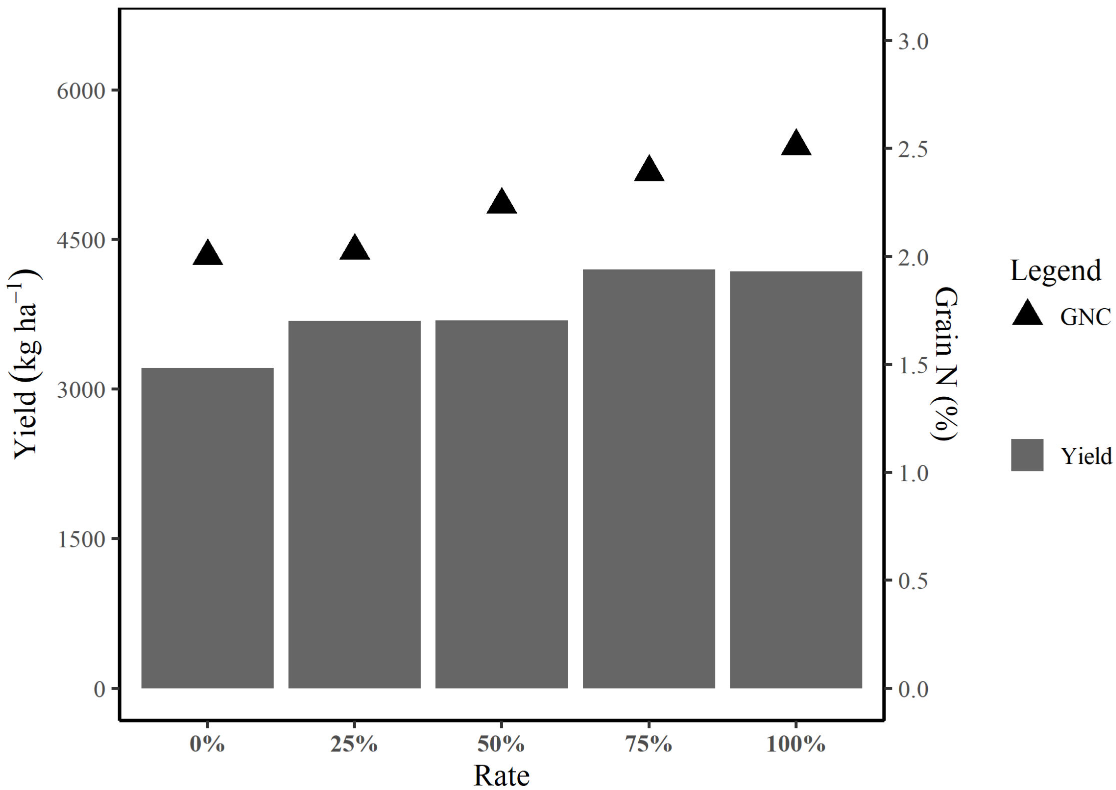


Figure 20 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Chickasha 1 location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

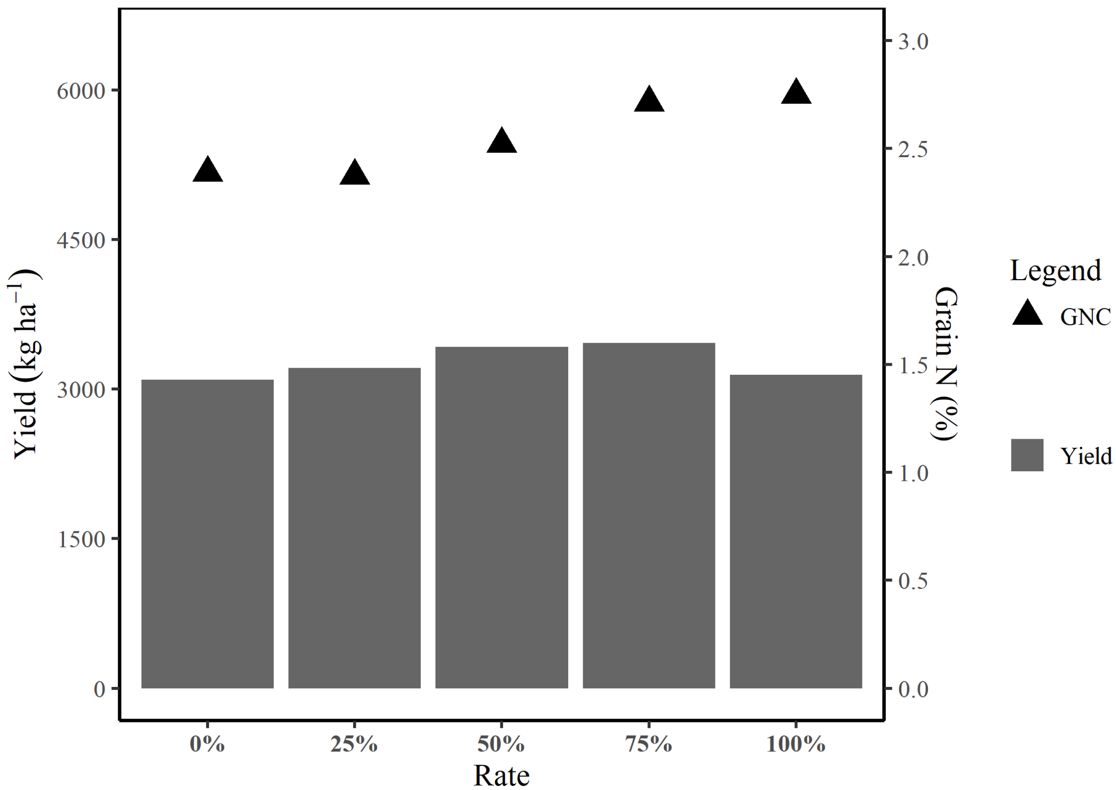


Figure 21 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Lahoma 1 location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

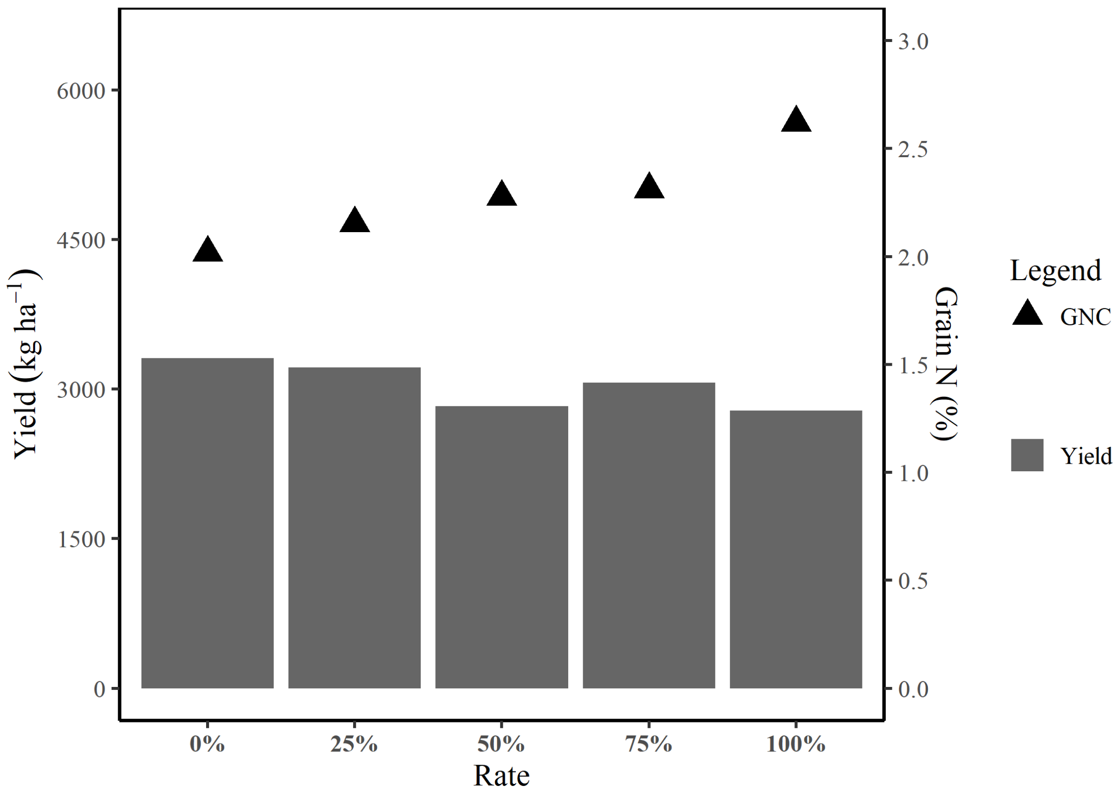


Figure 22 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Perkins location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

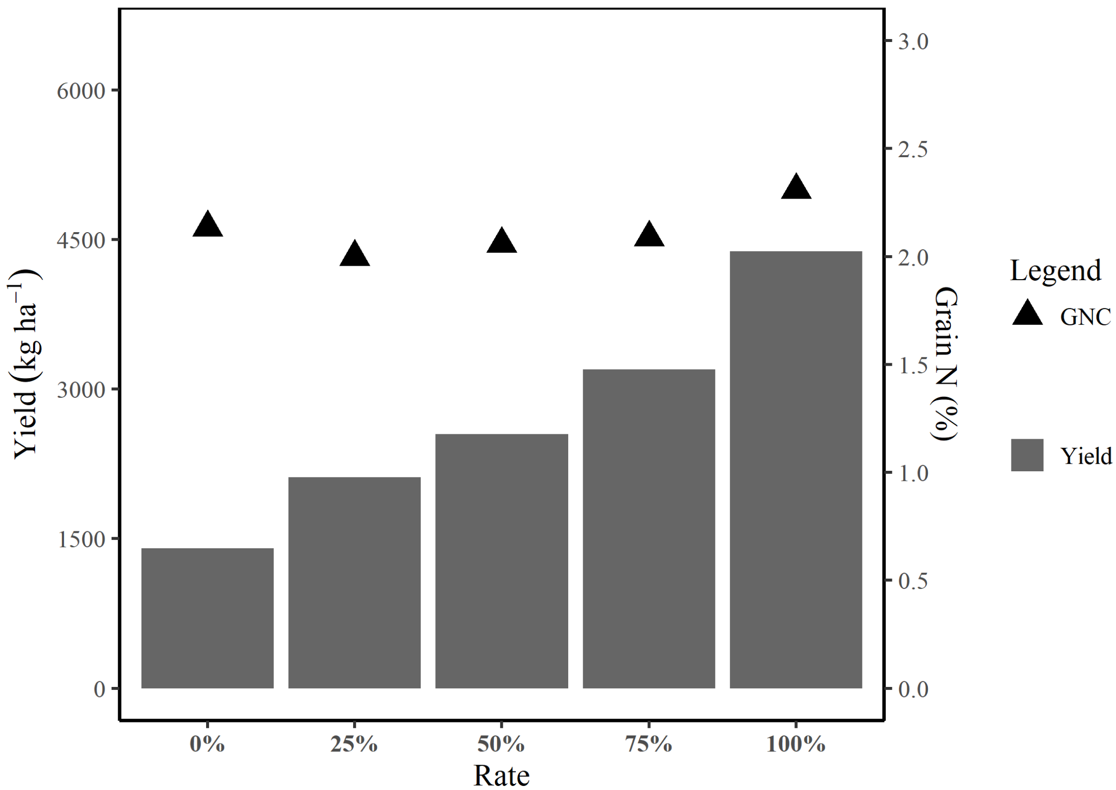


Figure 23 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Ballagh location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

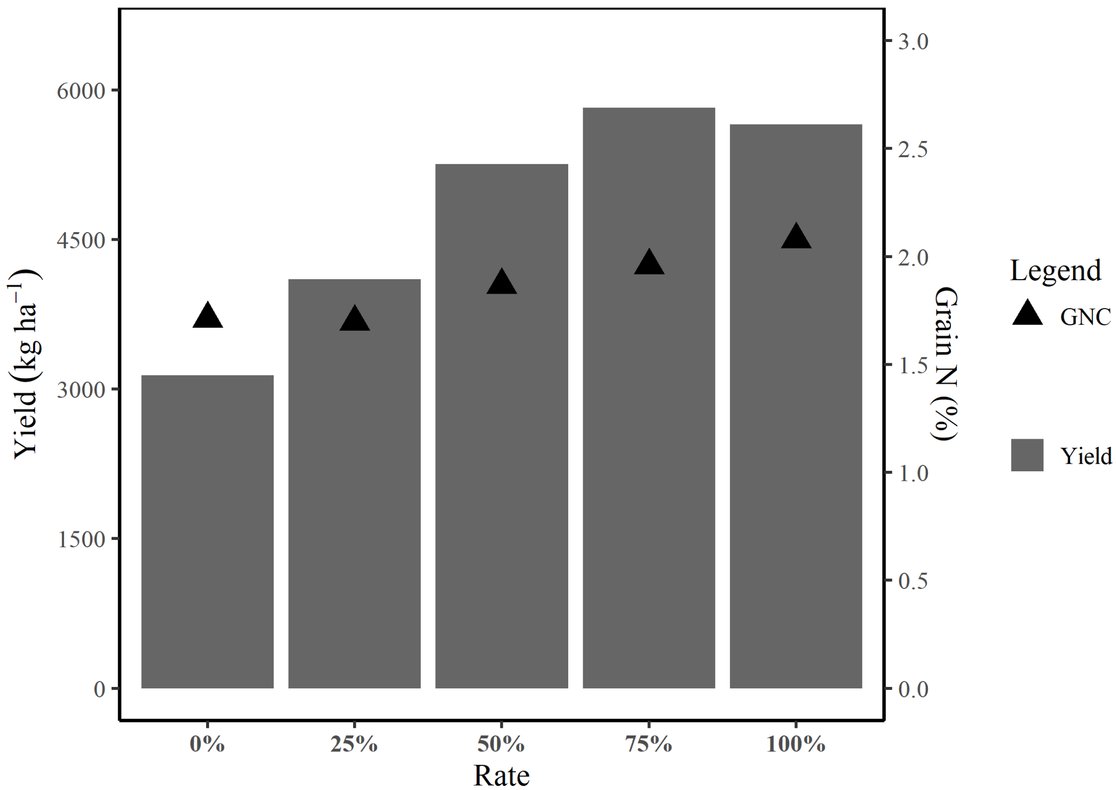


Figure 24 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Byron 2 location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

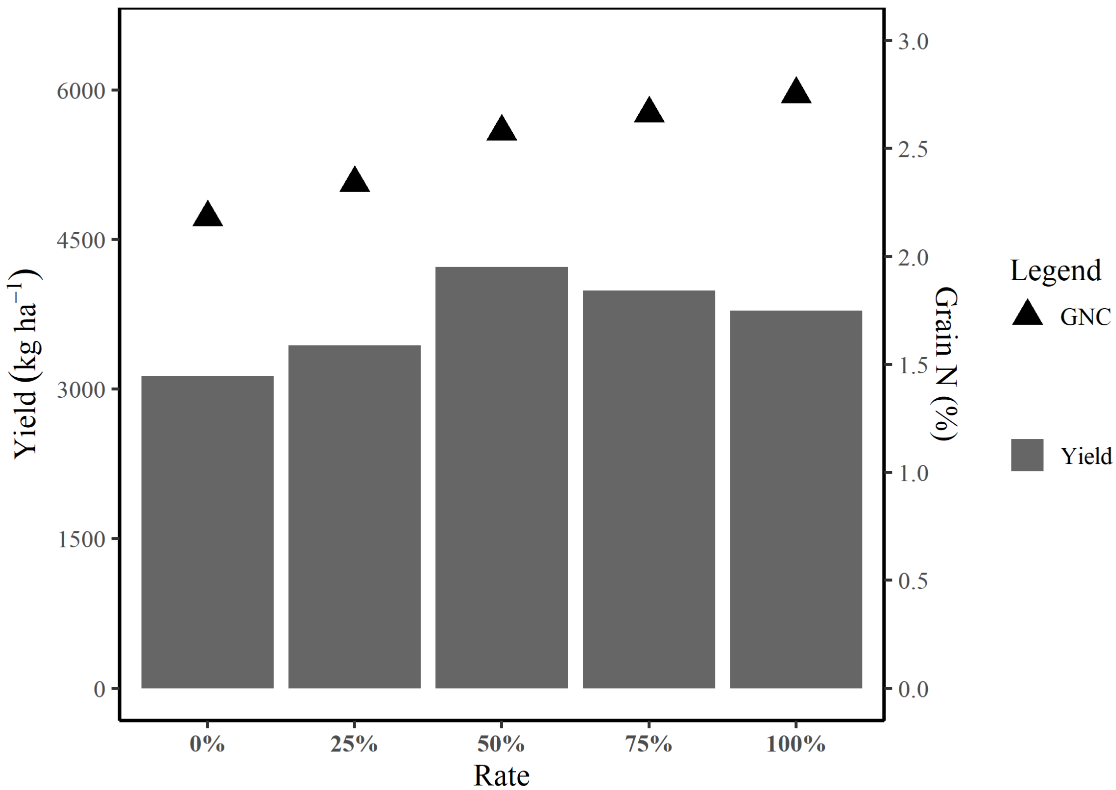


Figure 25 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Byron 3 location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

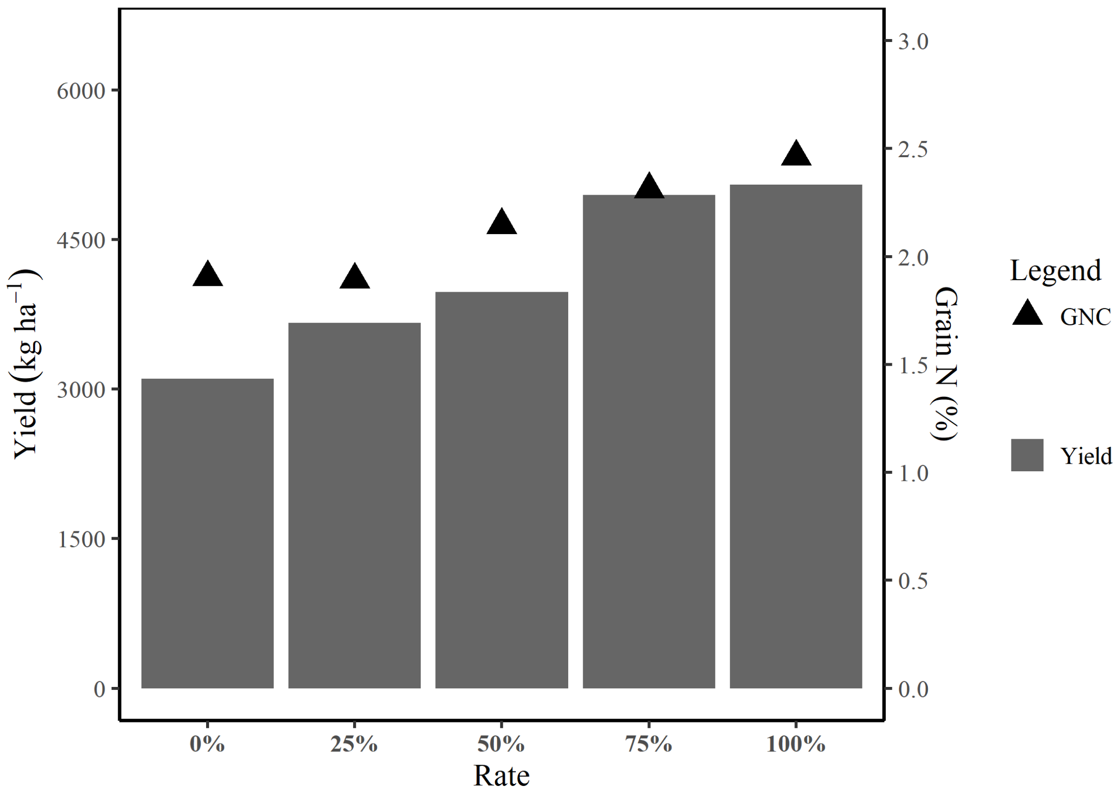


Figure 26 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Carmen location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

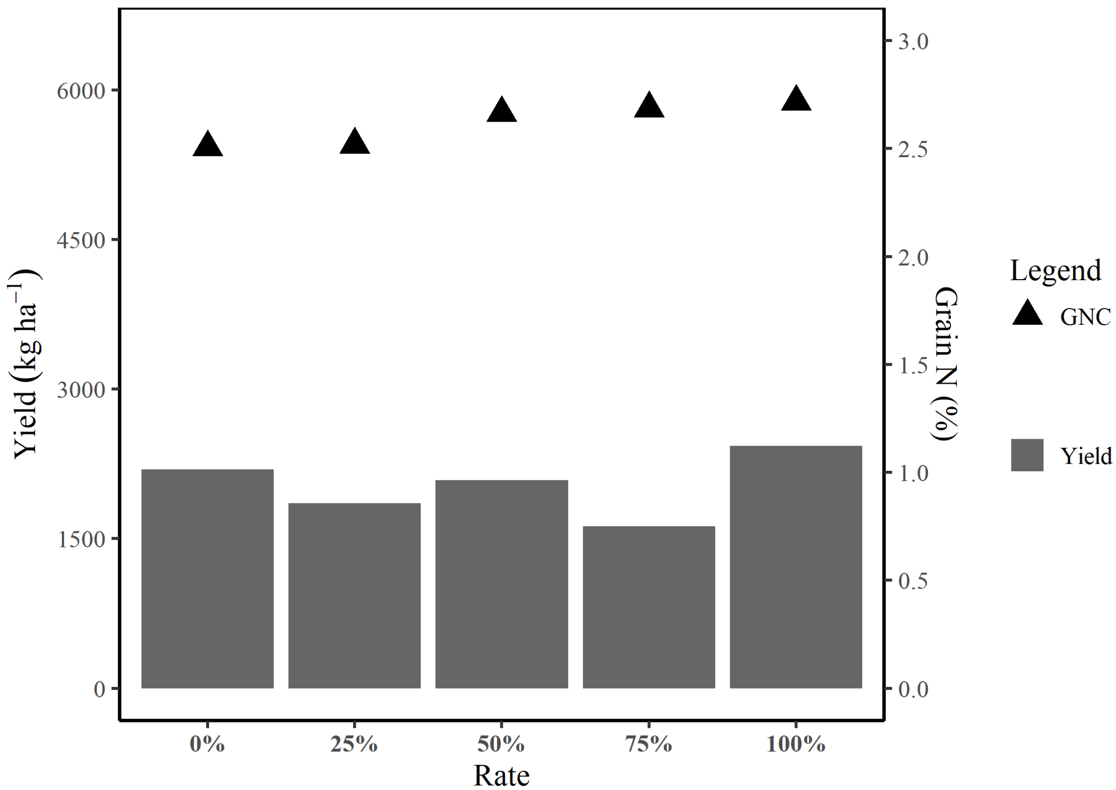


Figure 27 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Chickasha 2 location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

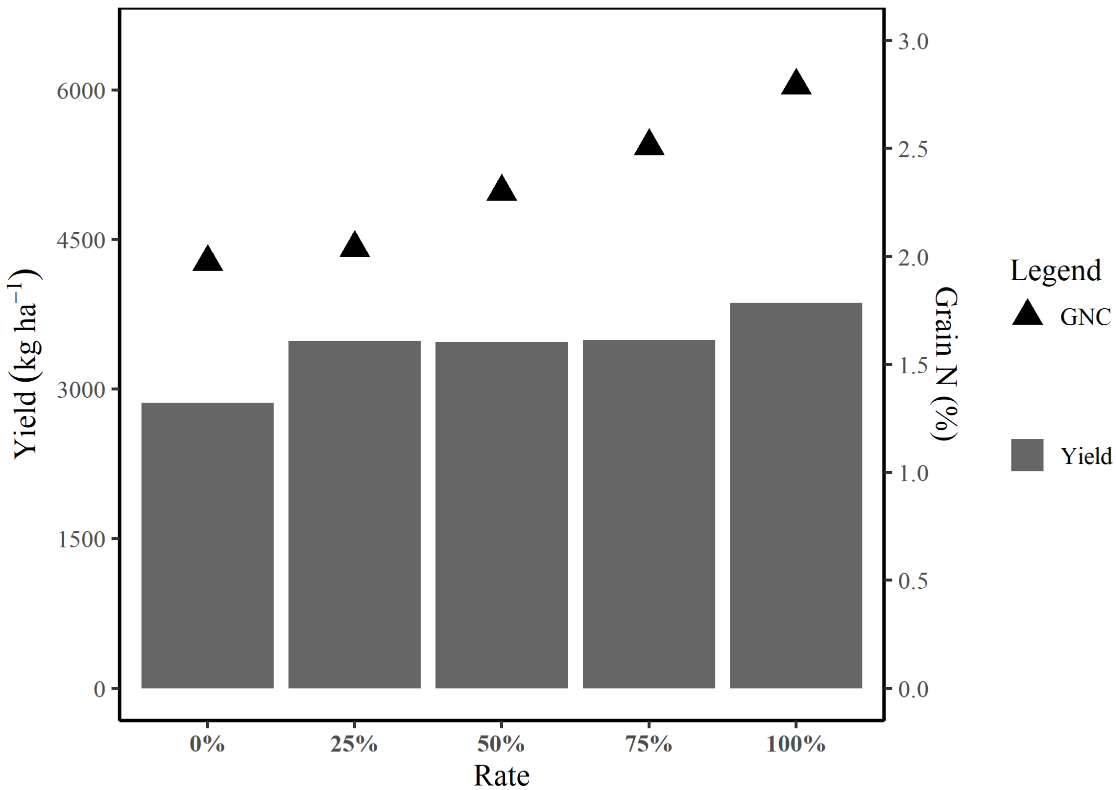


Figure 28 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Dove location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

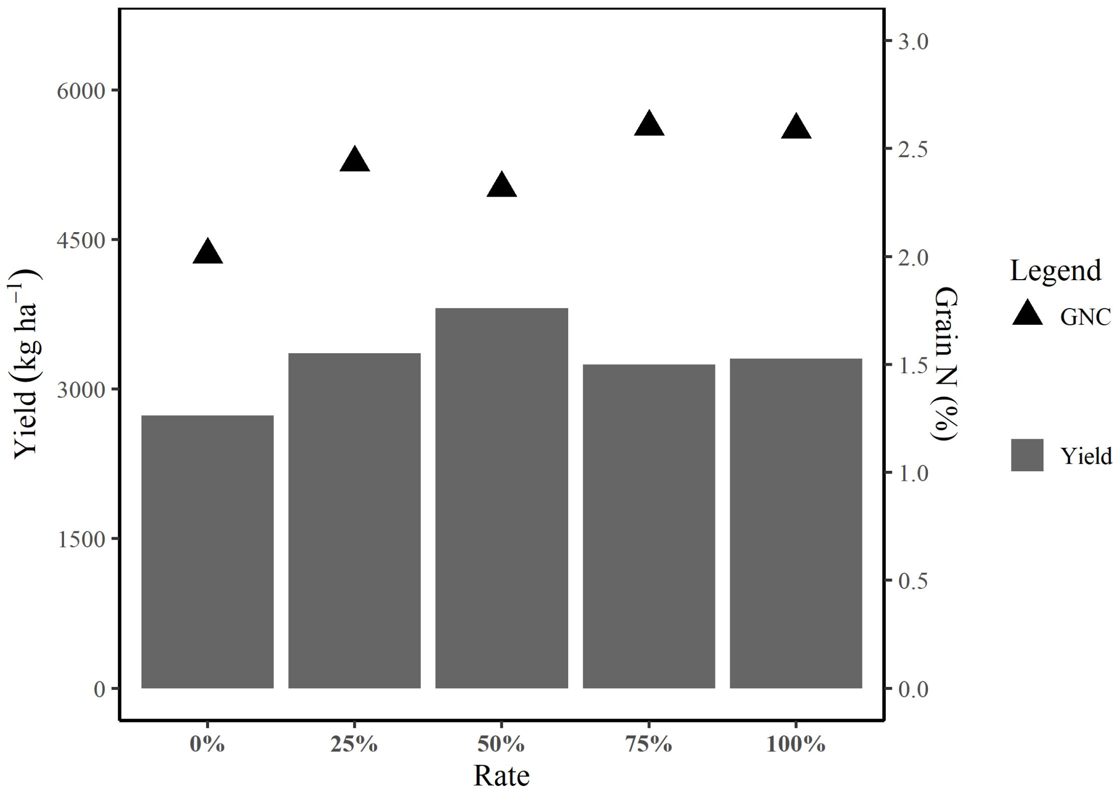


Figure 29 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the El Reno location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

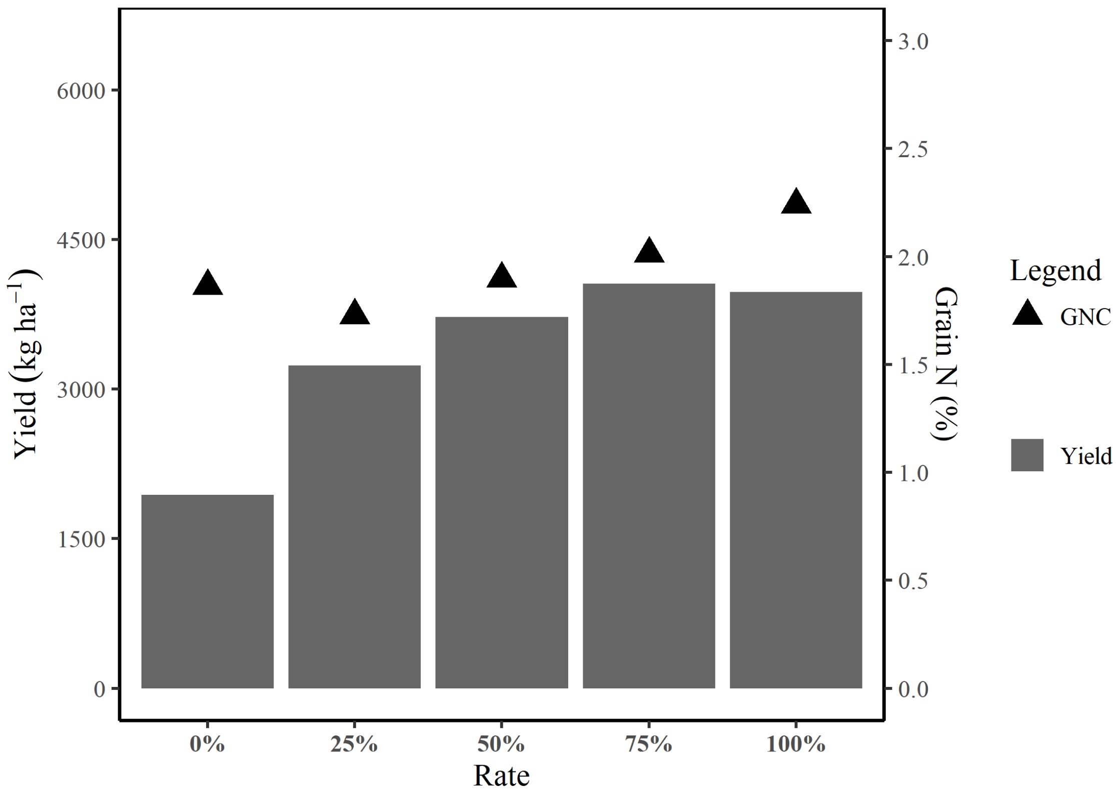


Figure 30 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Elmwood location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

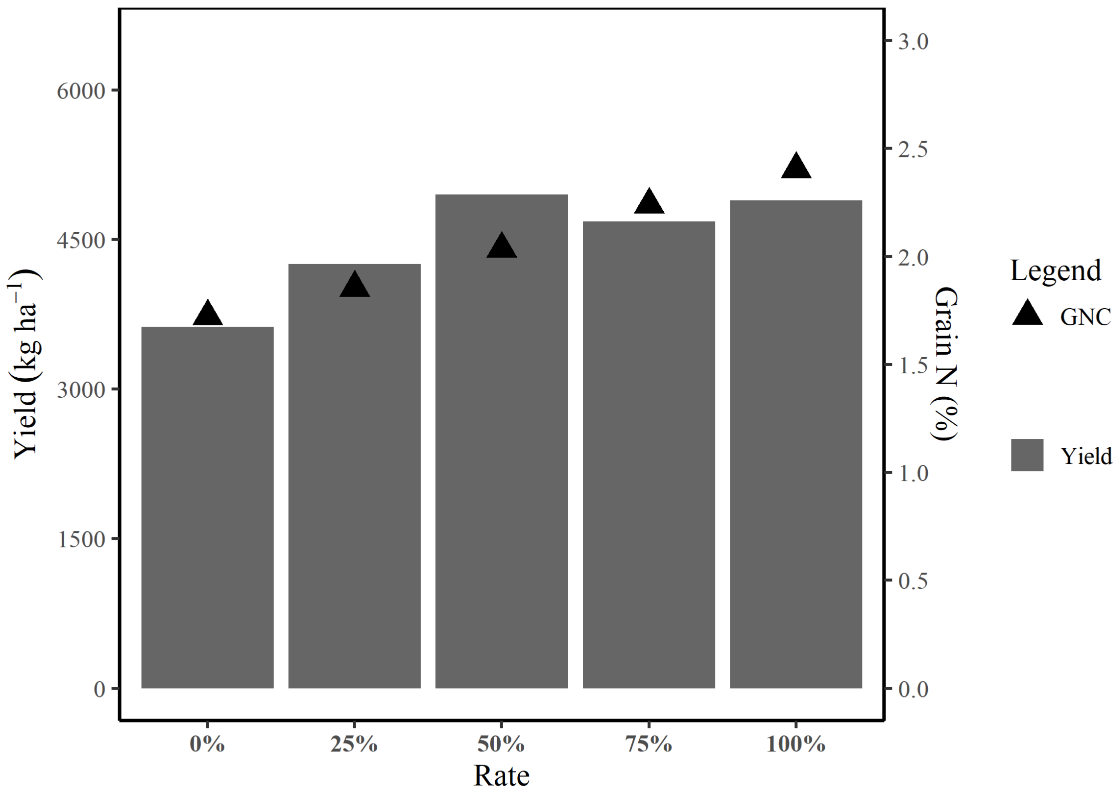


Figure 31 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Granite location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

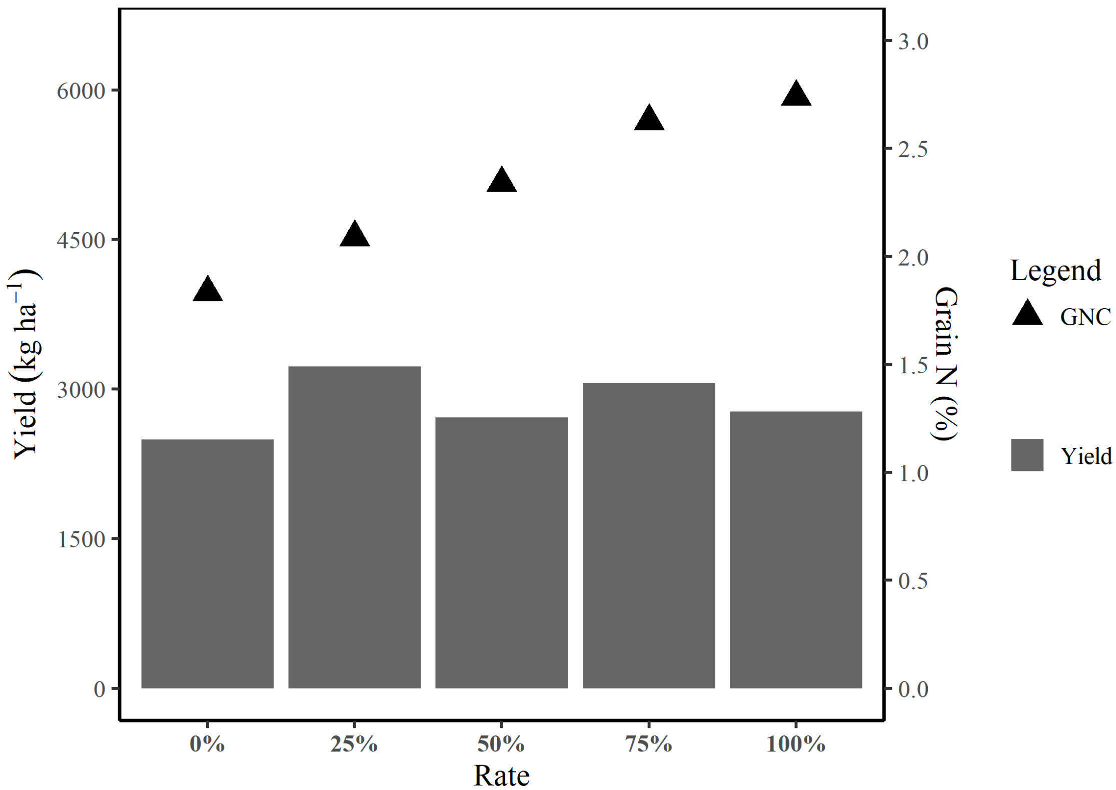


Figure 32 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Hobart location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

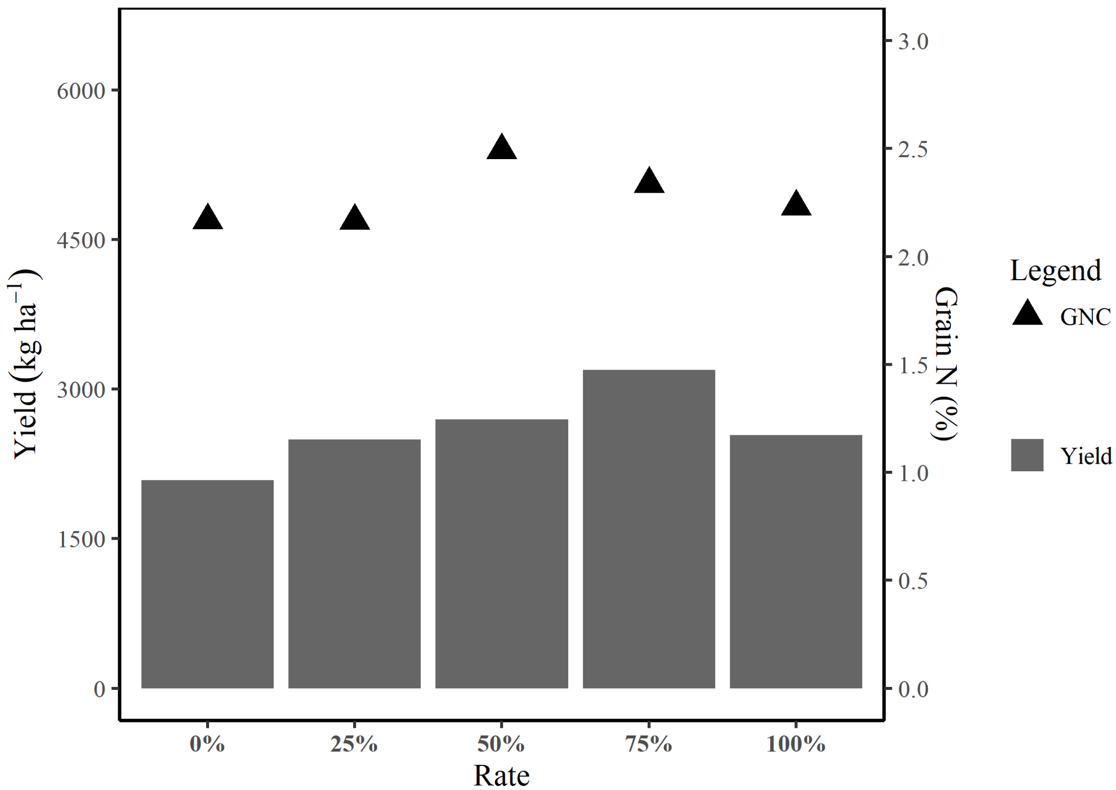


Figure 33 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Lahoma 2 location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

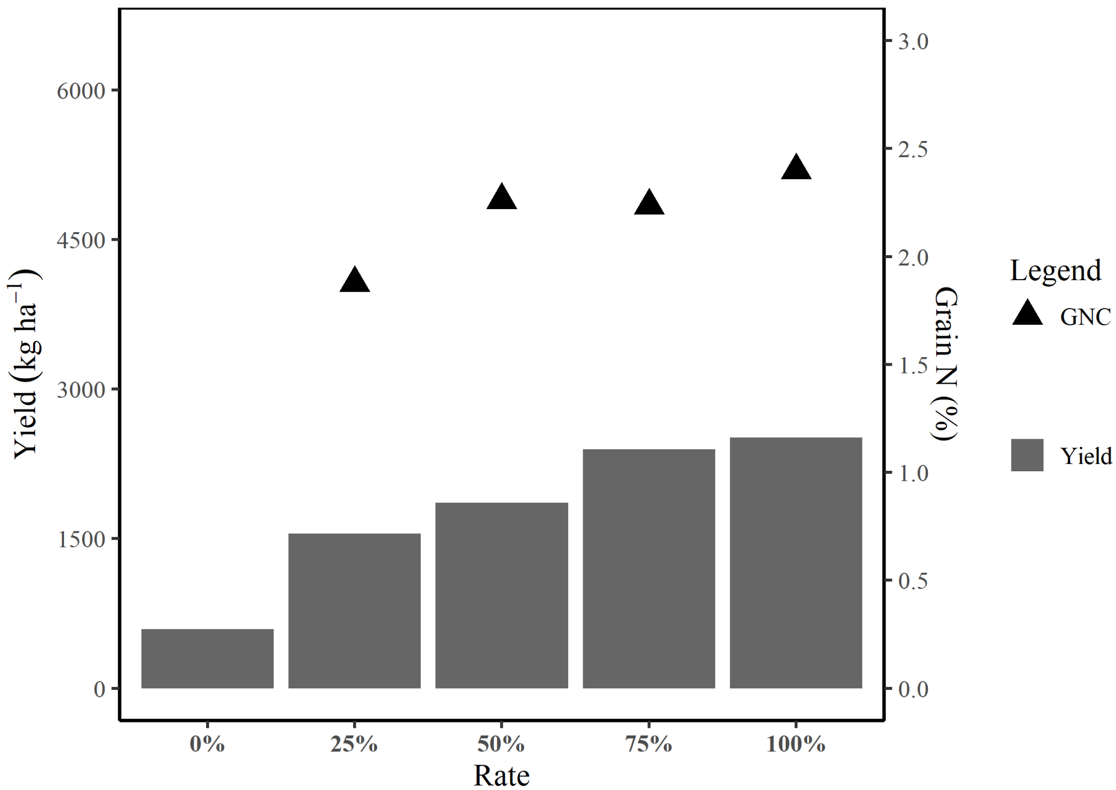


Figure 34 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the LCB location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

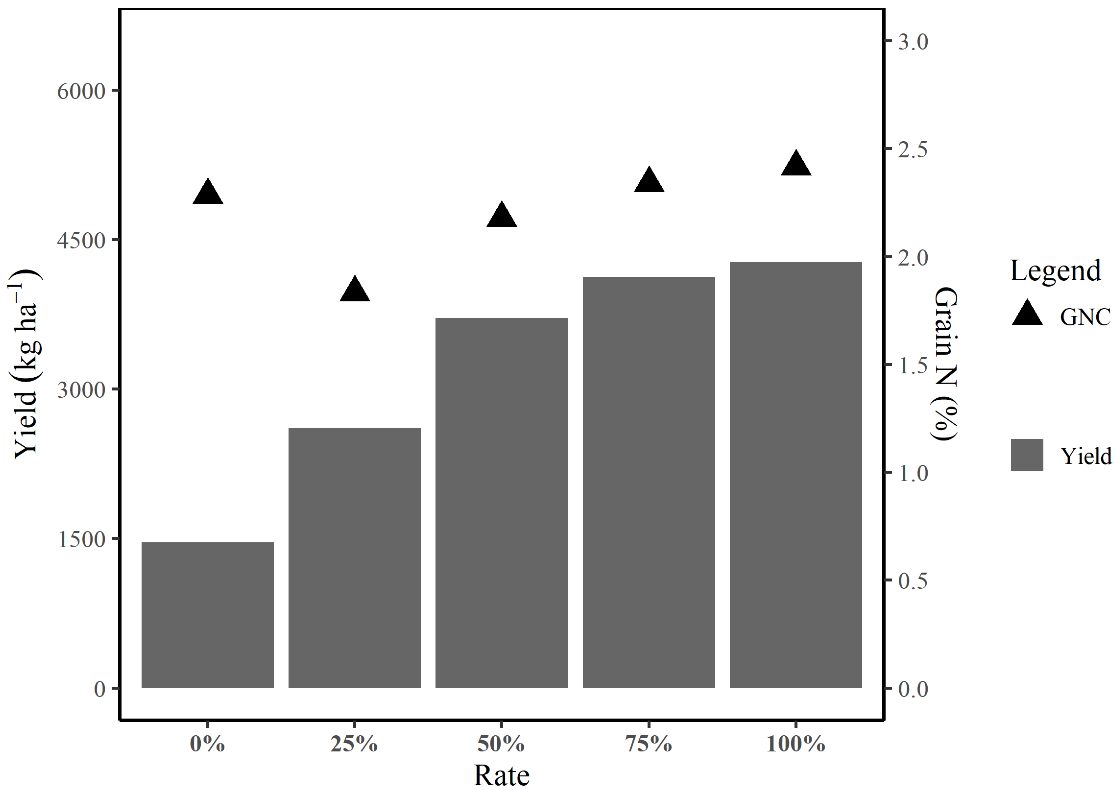


Figure 35 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Nardin location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

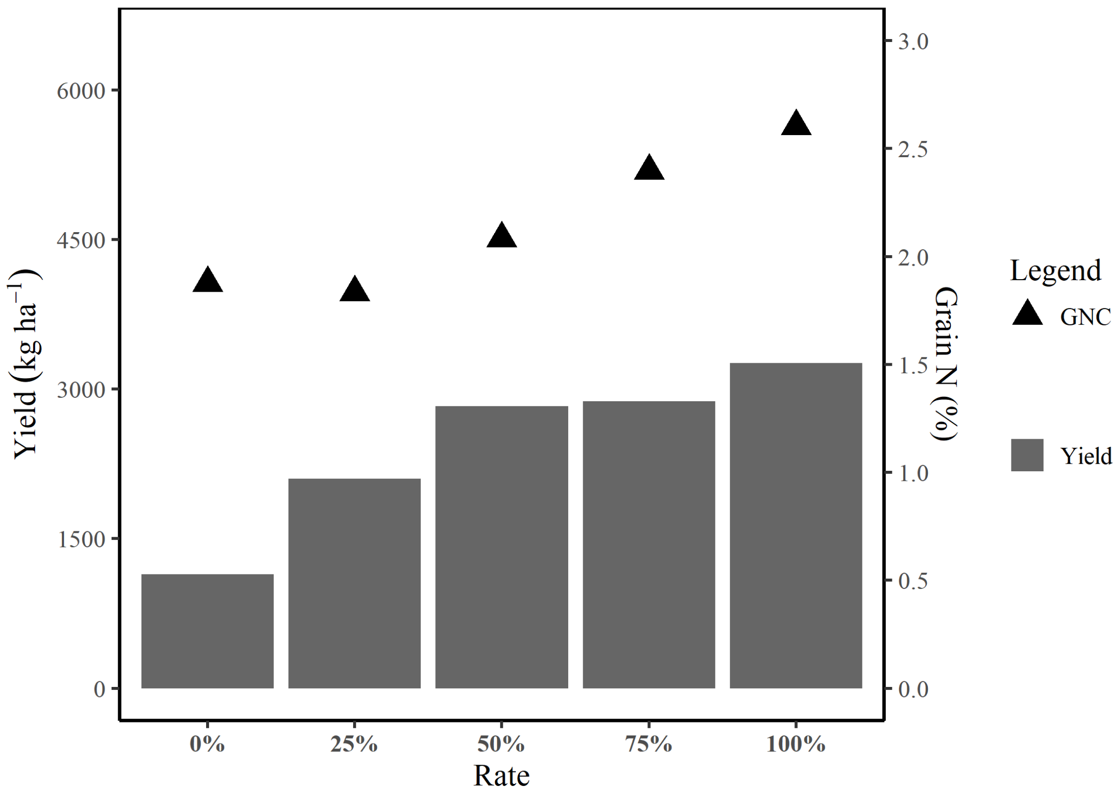


Figure 36 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Tipton location for each rate. Rate is presented as a percentage. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

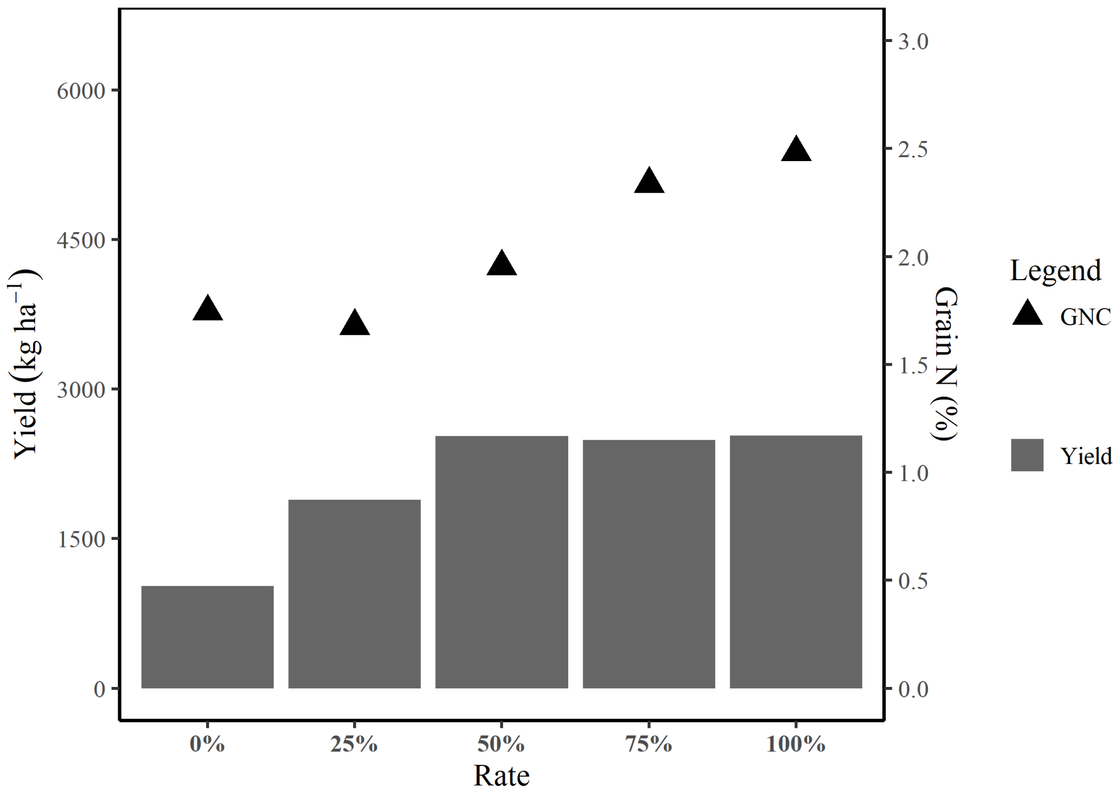


Figure 37 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Byron 1 location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

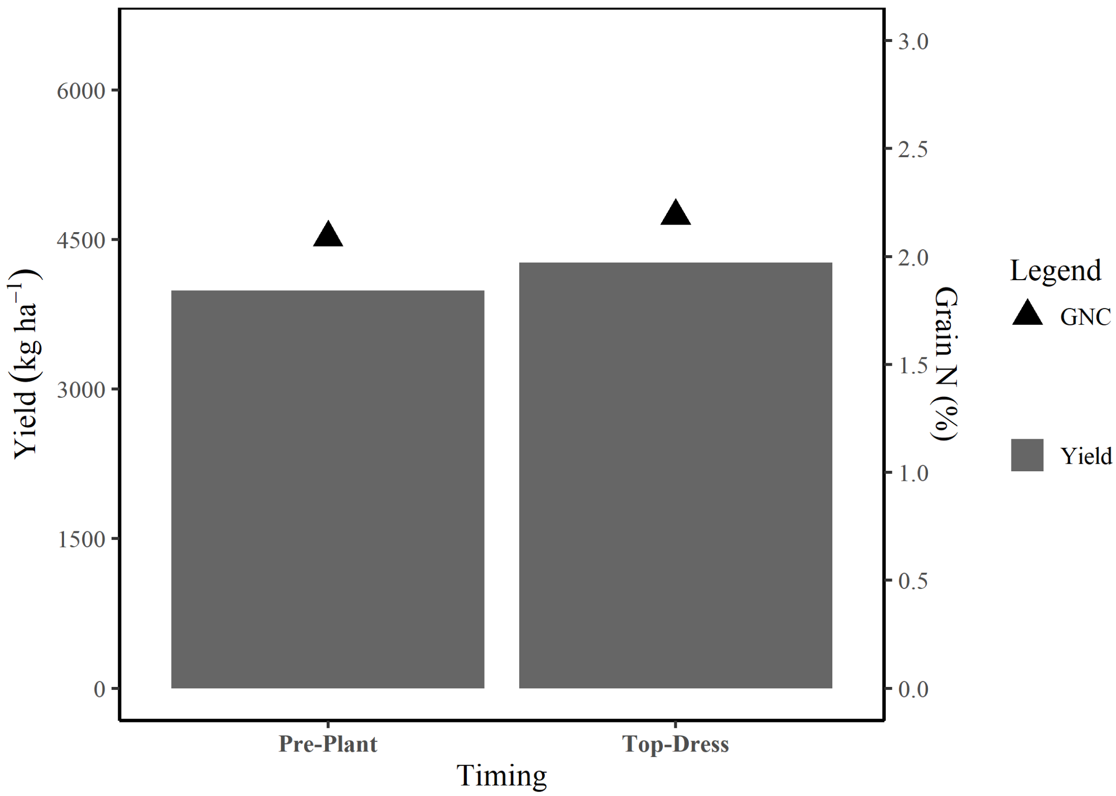


Figure 38 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Capron location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

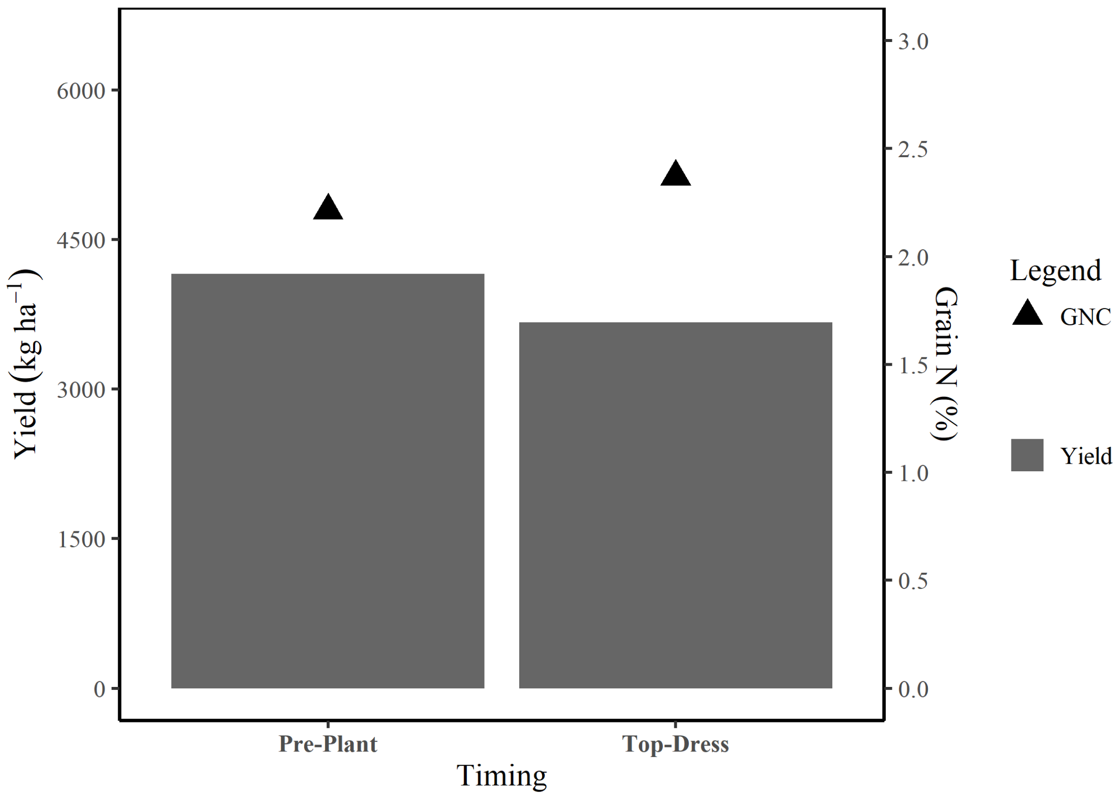


Figure 39 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Lahoma 1 location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

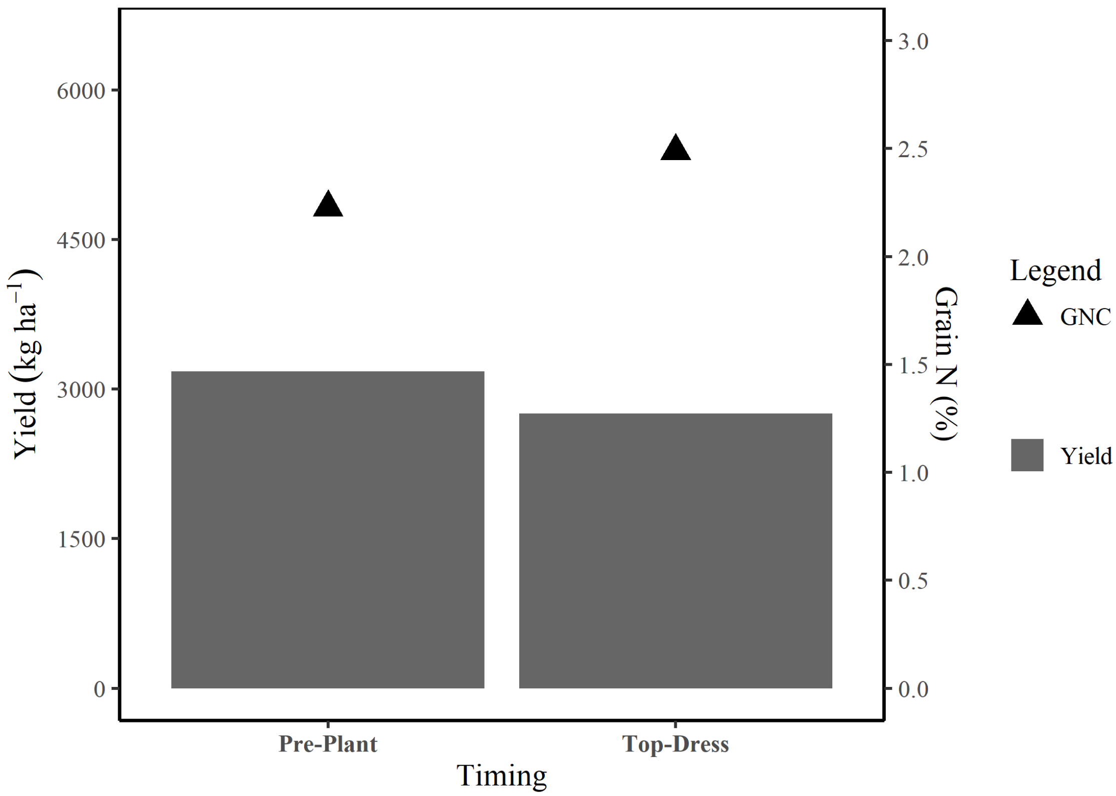


Figure 40 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Perkins location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

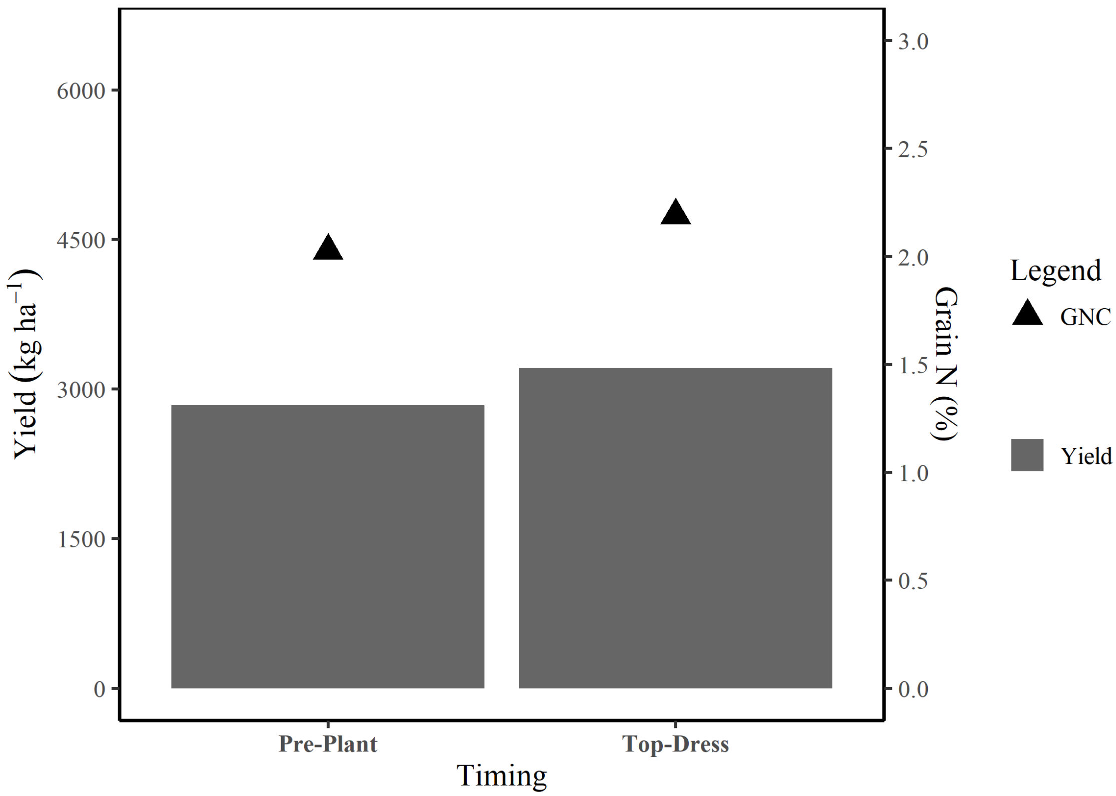


Figure 41 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Ballagh location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

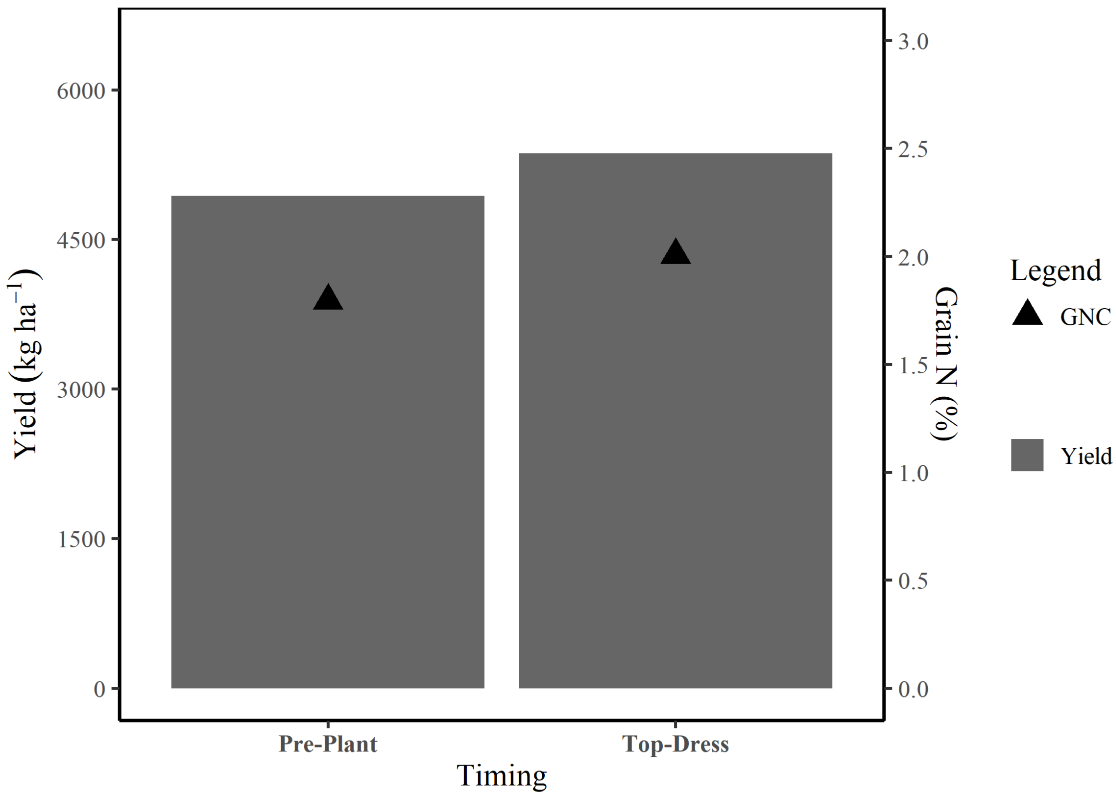


Figure 42 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Byron 2 location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

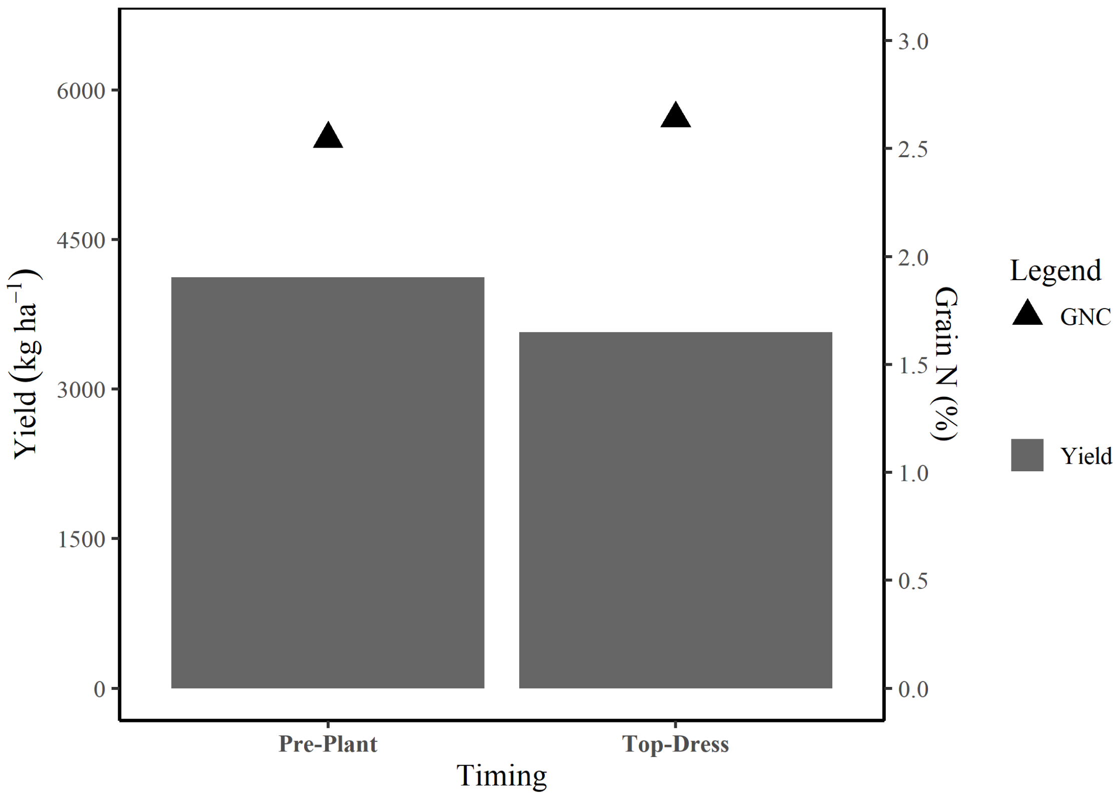


Figure 43 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Byron 3 location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

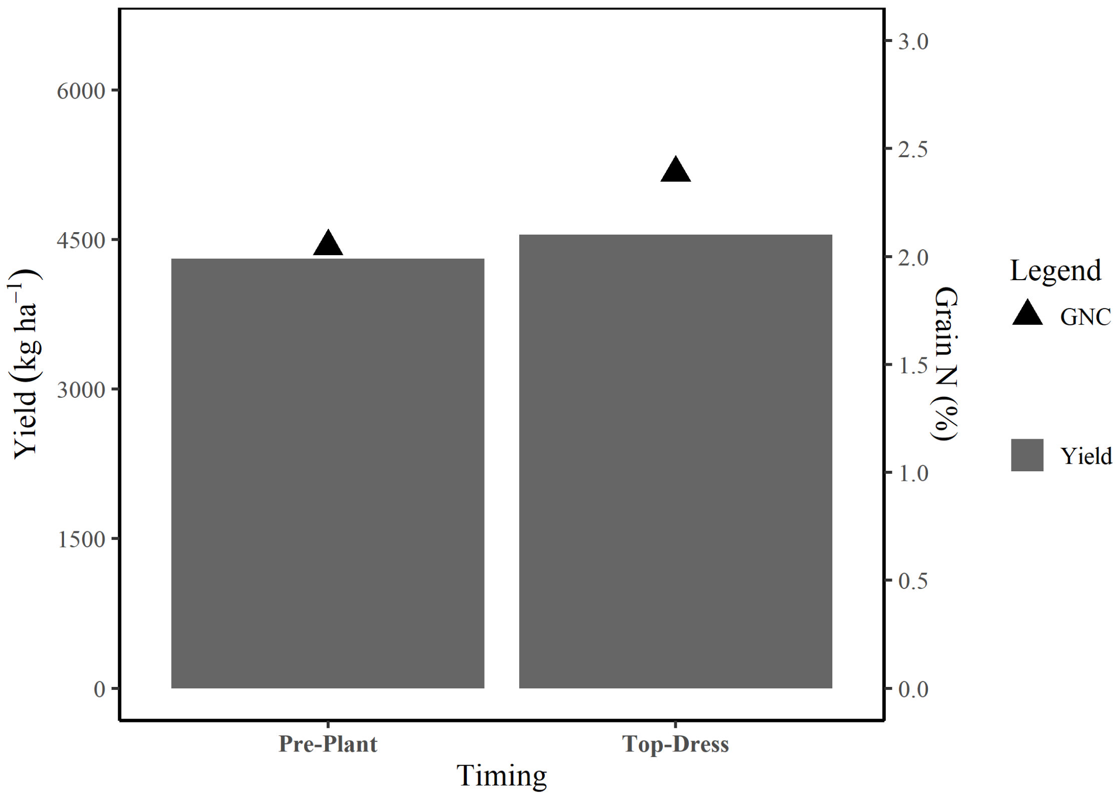


Figure 44 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Carmen location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

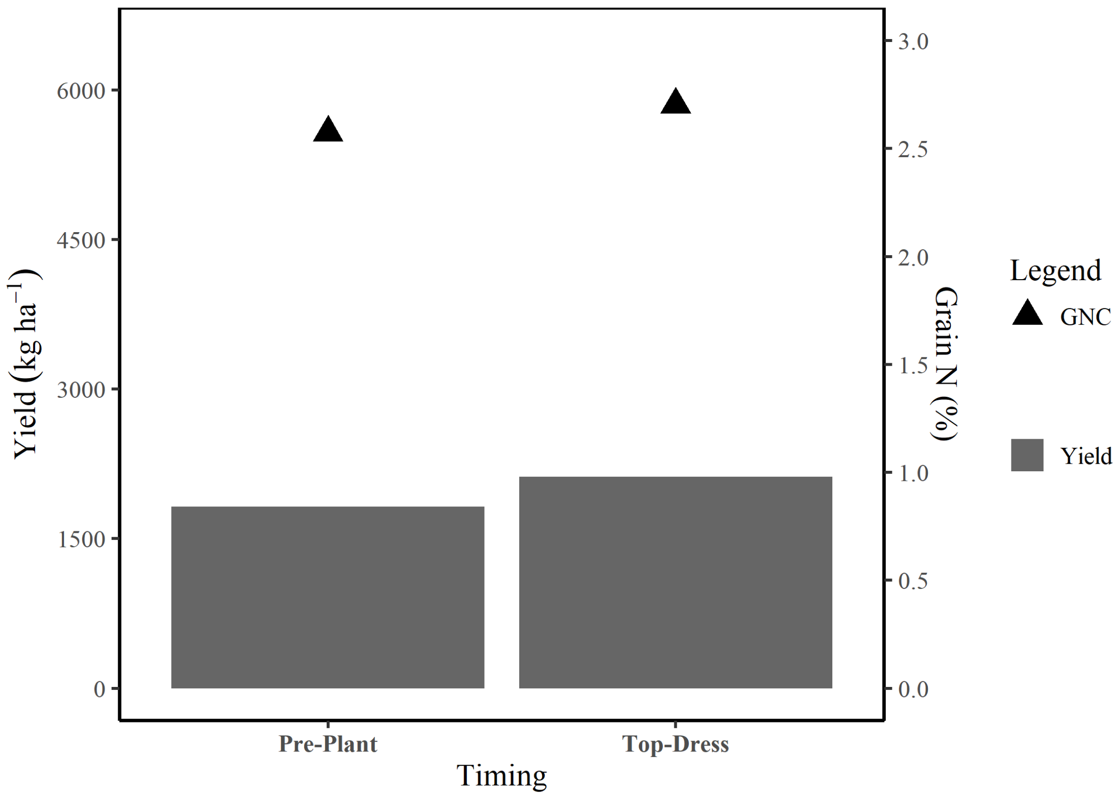


Figure 45 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Chickasha 2 location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

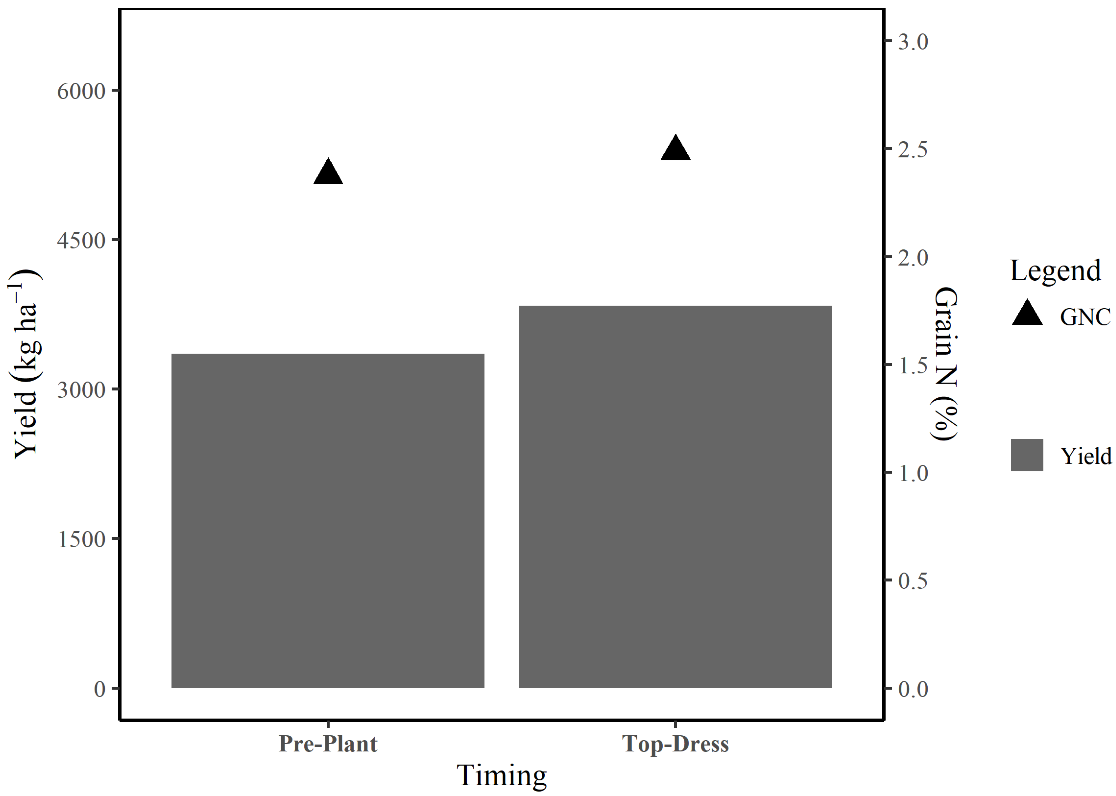


Figure 46 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Dove location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

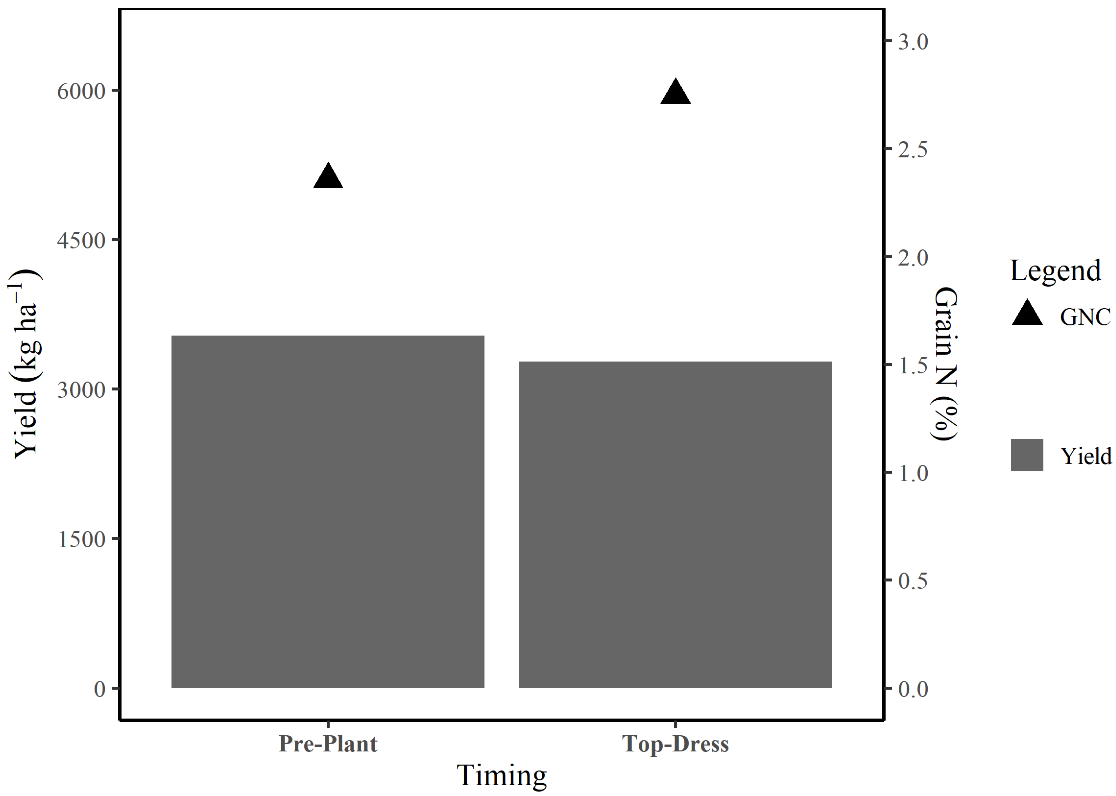


Figure 47 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the El Reno location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

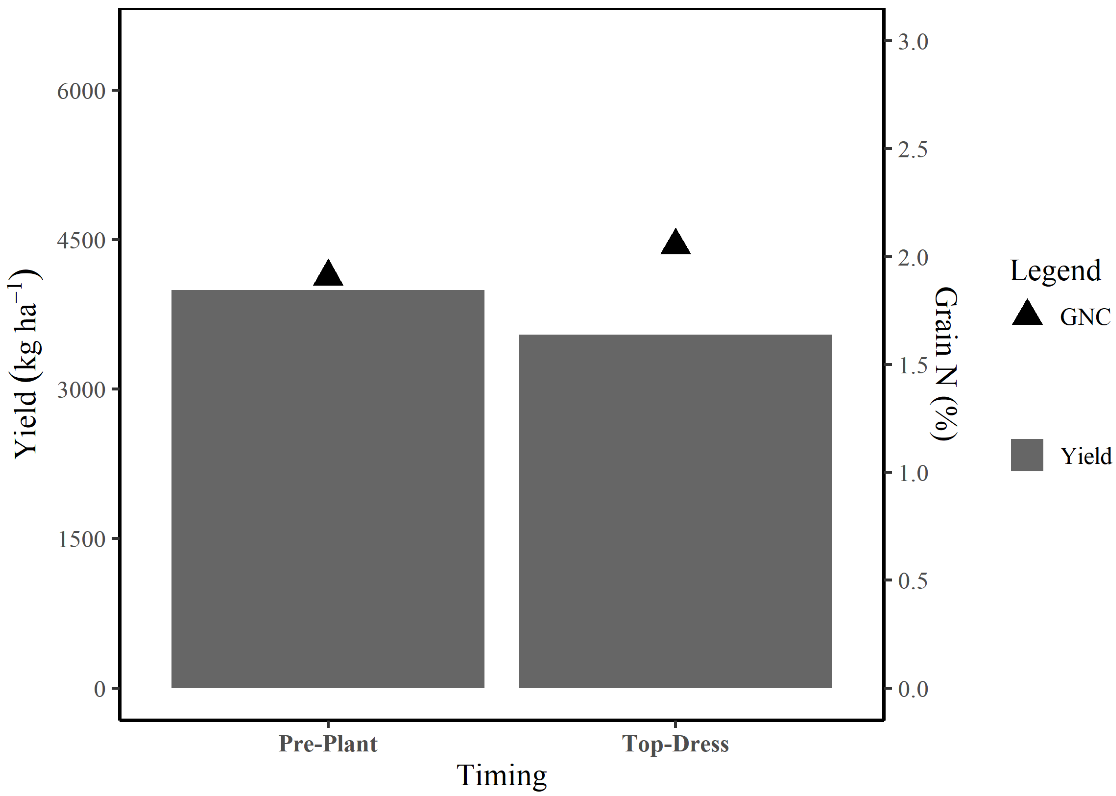


Figure 48 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Elmwood location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

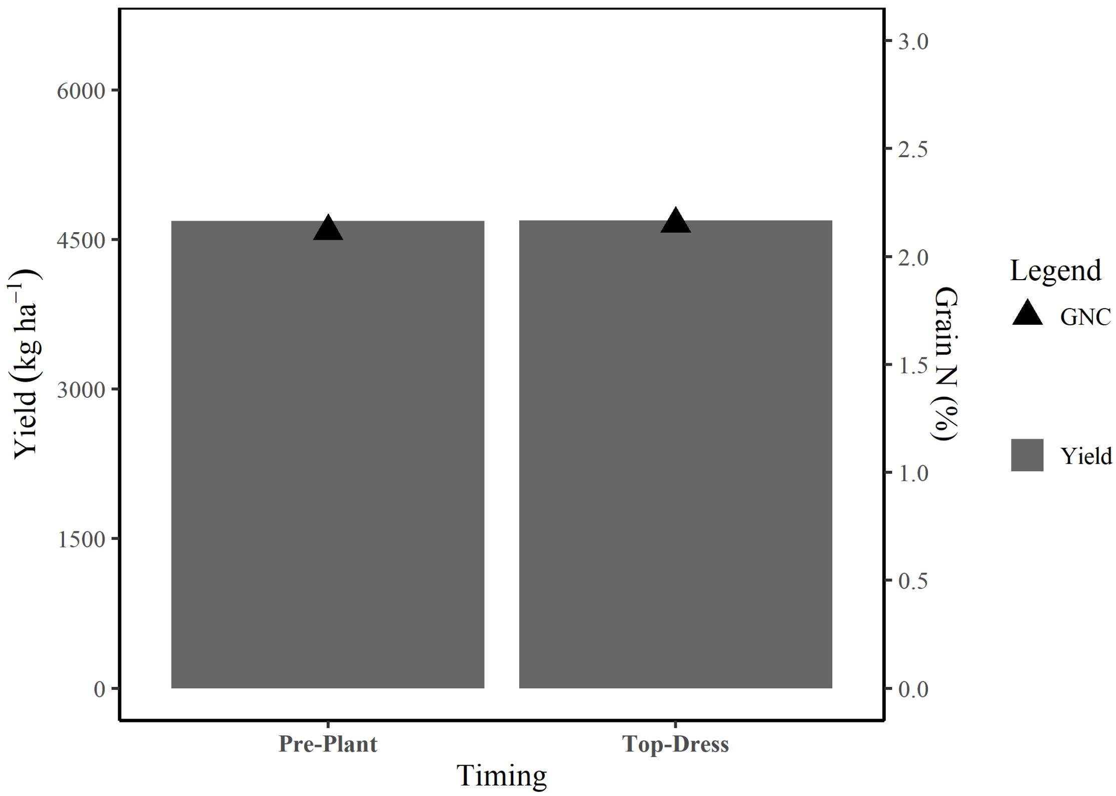


Figure 49 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Granite location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

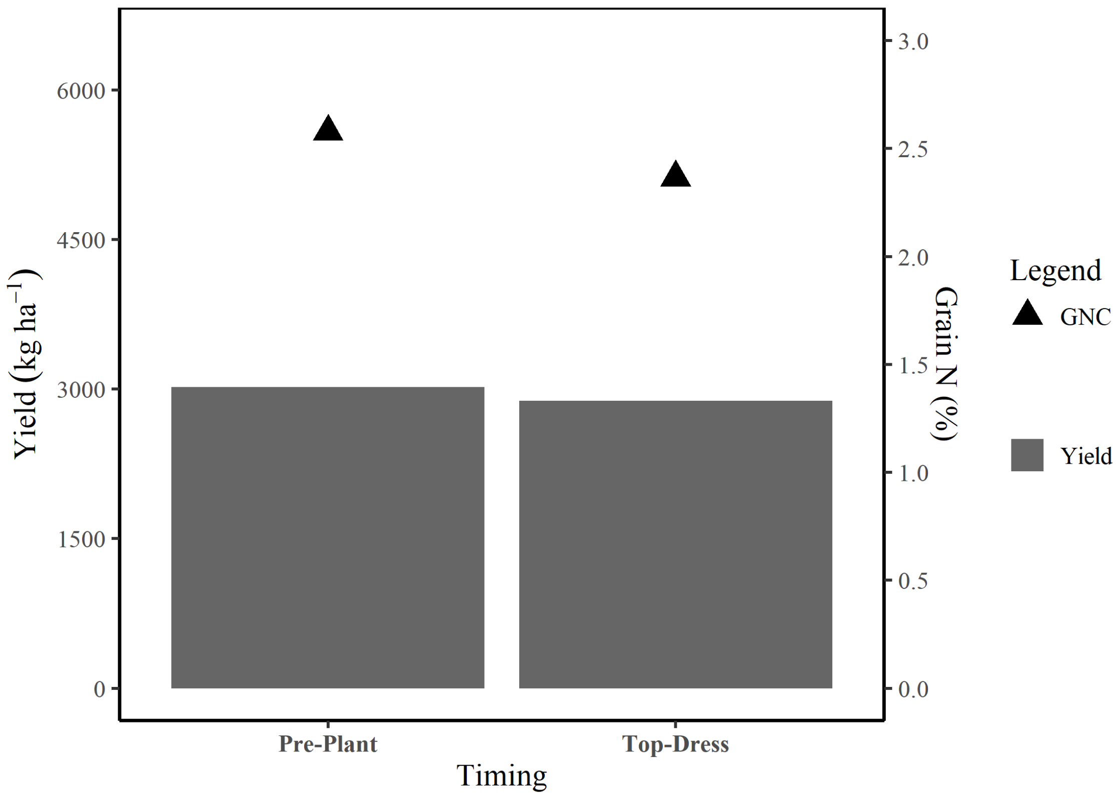


Figure 50 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Hobart location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

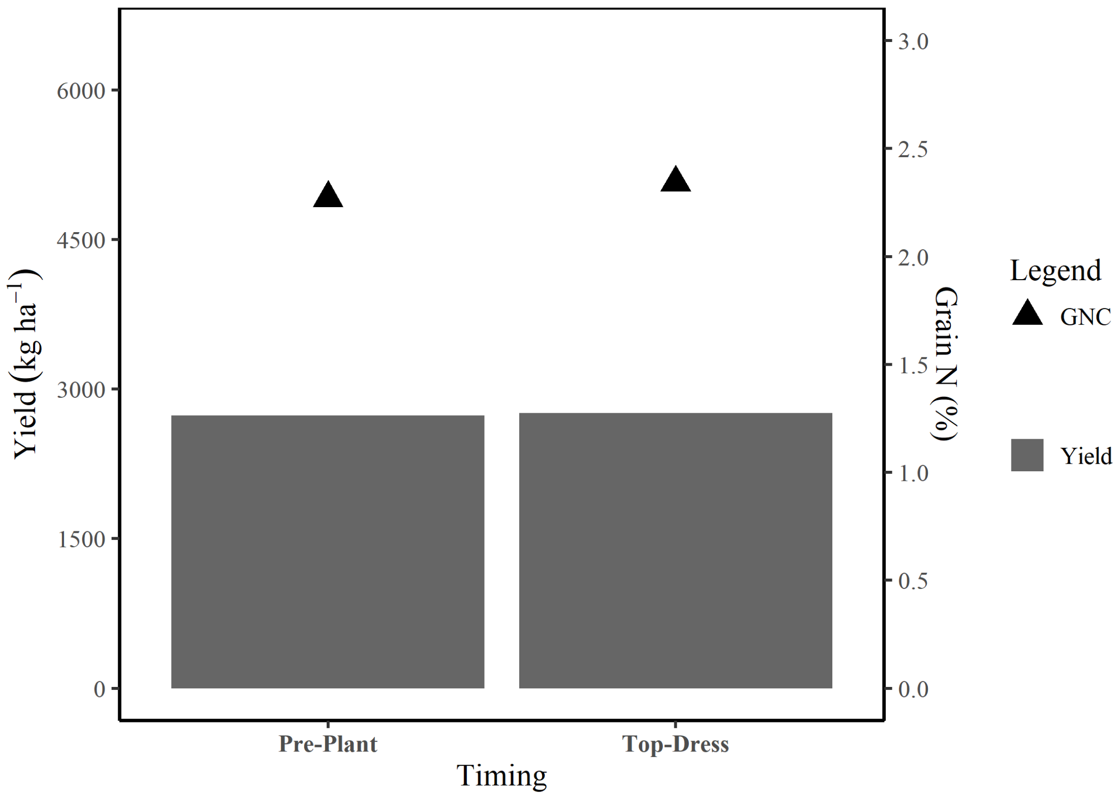


Figure 51 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Lahoma 2 location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

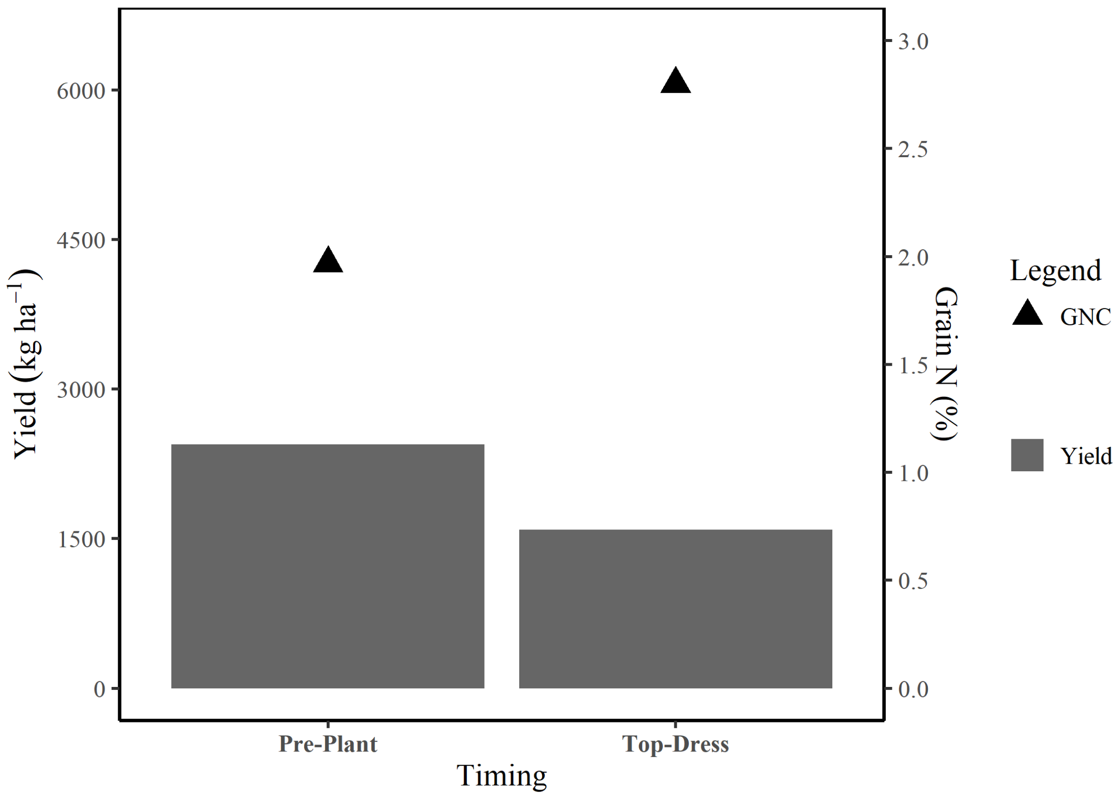


Figure 52 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the LCB location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

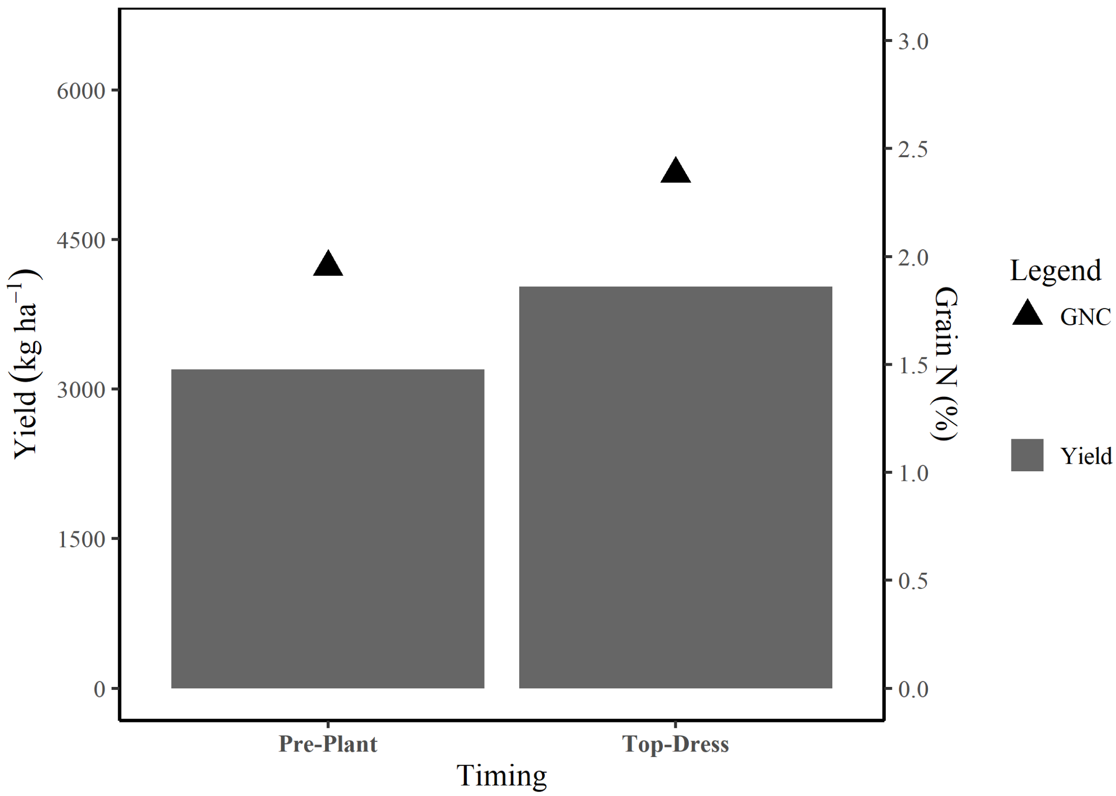


Figure 53 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Nardin location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

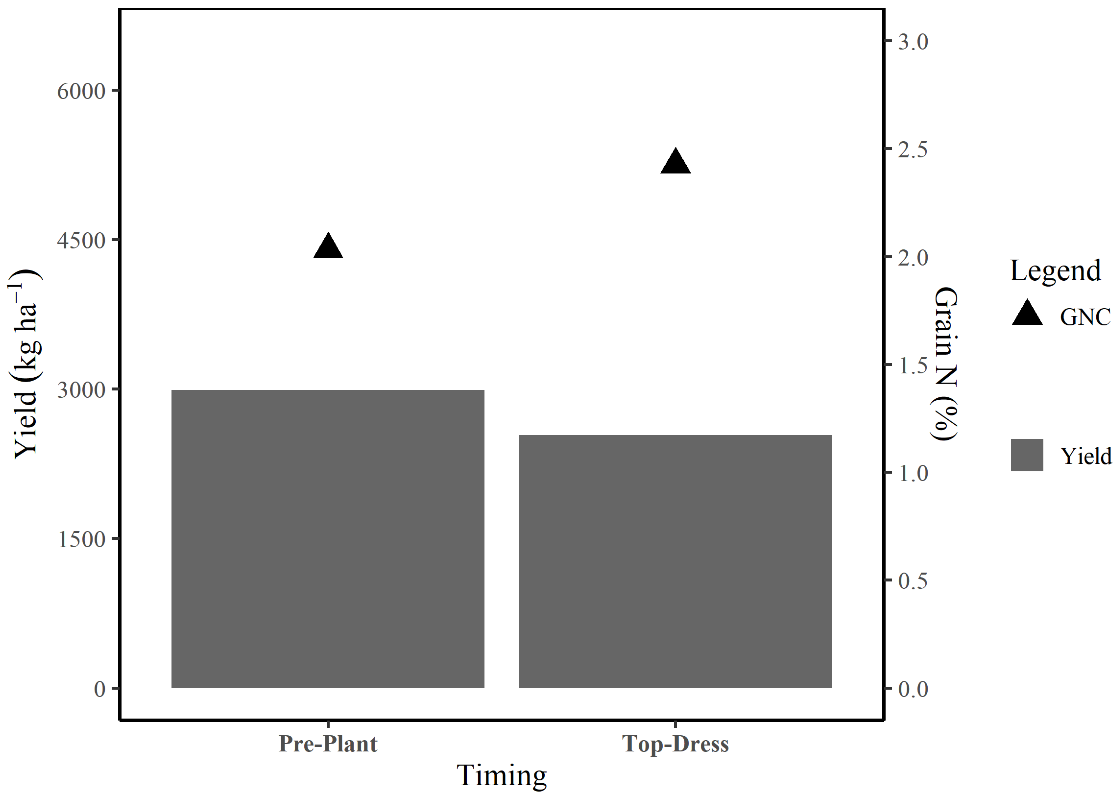


Figure 54 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Tipton location for each timing. Timing applications were either pre-plant or top-dress applications. Top-dress applications were aimed to be applied between 80-110 GDD>0, prior to Feekes 5 growth stage.

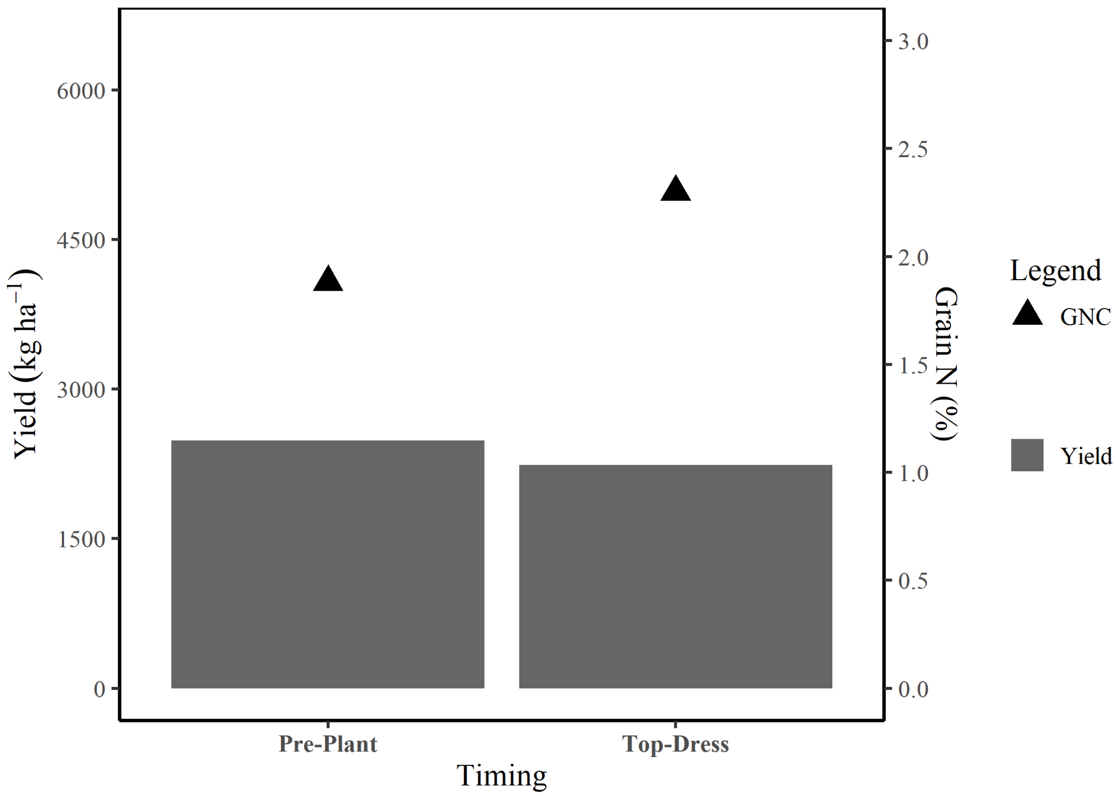


Figure 55 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Byron 1 location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

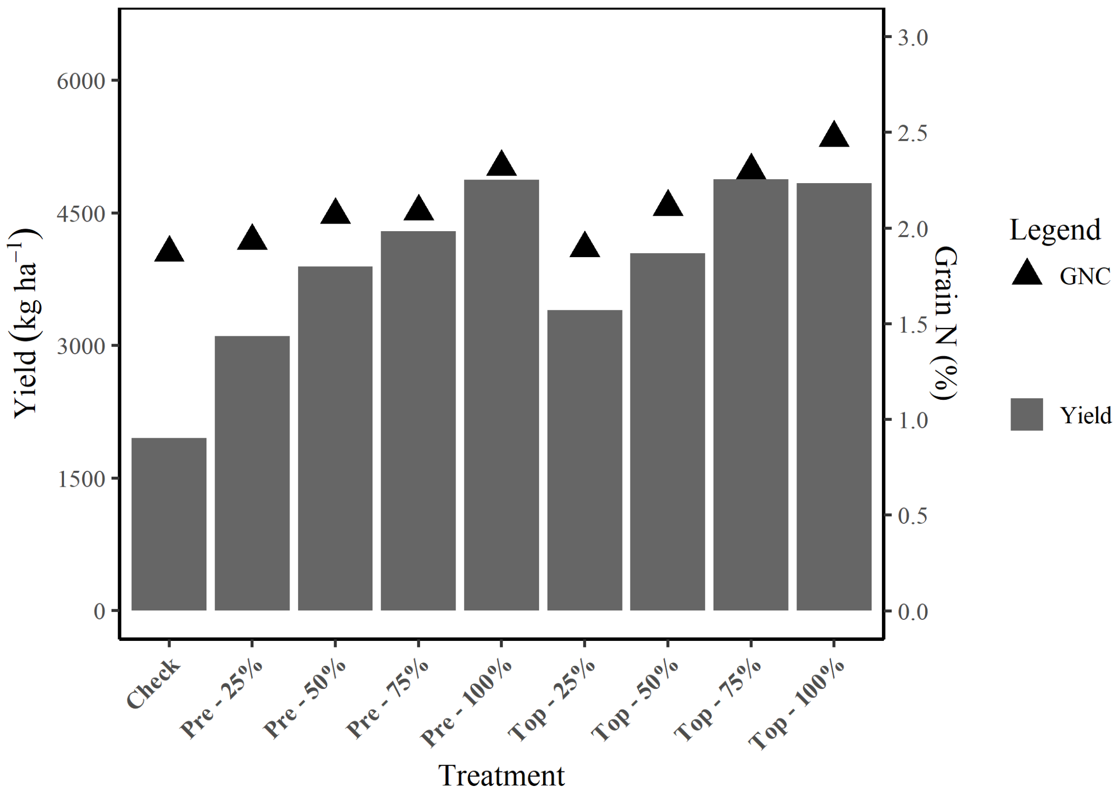


Figure 56 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Capron location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

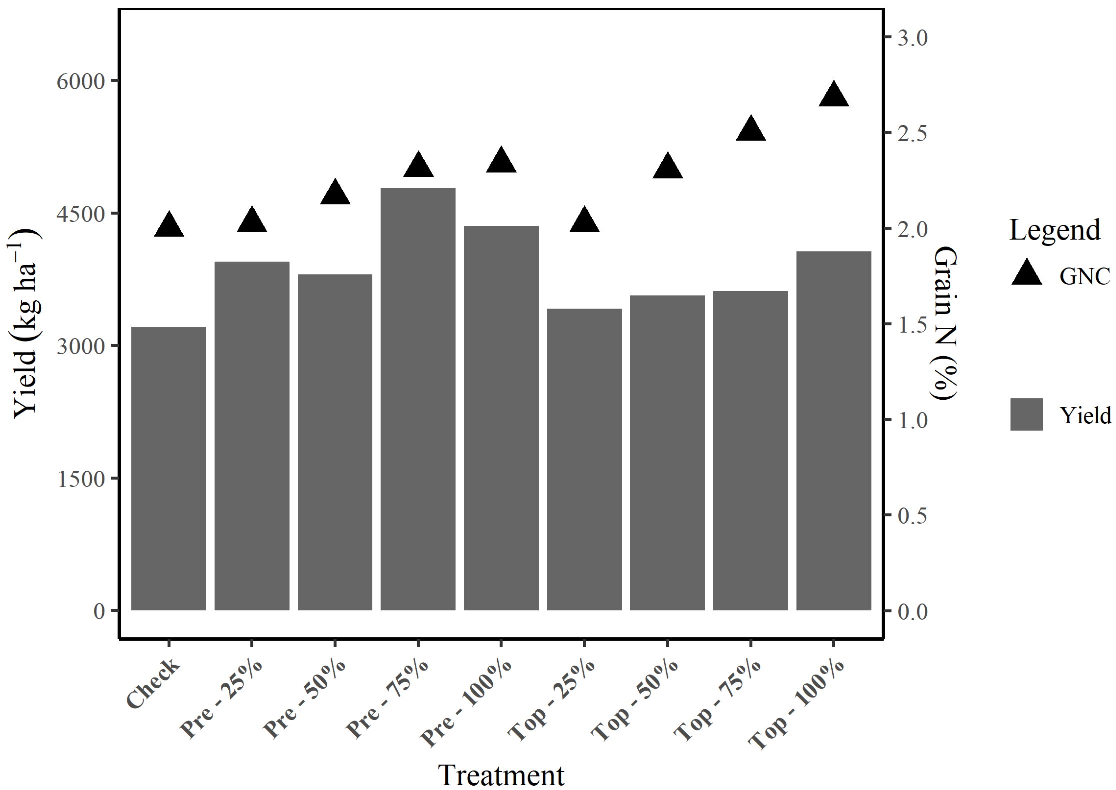


Figure 57 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Chickasha 1 location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

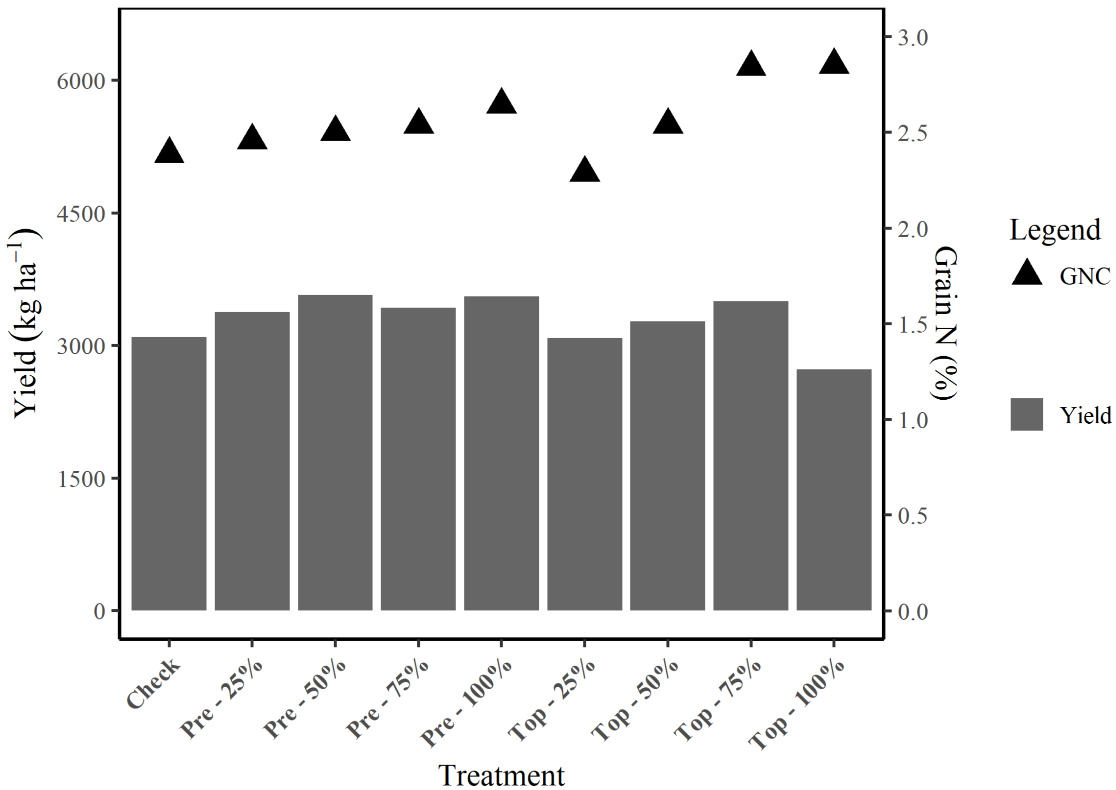


Figure 58 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Lahoma 1 location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

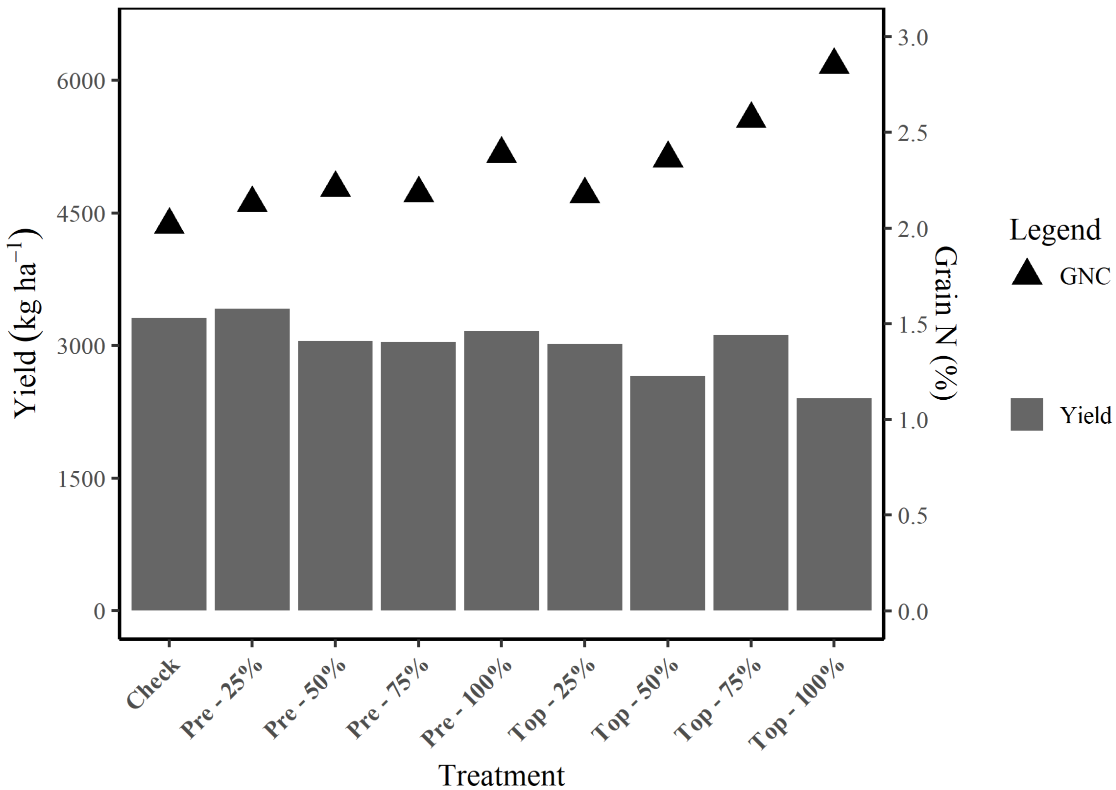


Figure 59 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Perkins location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

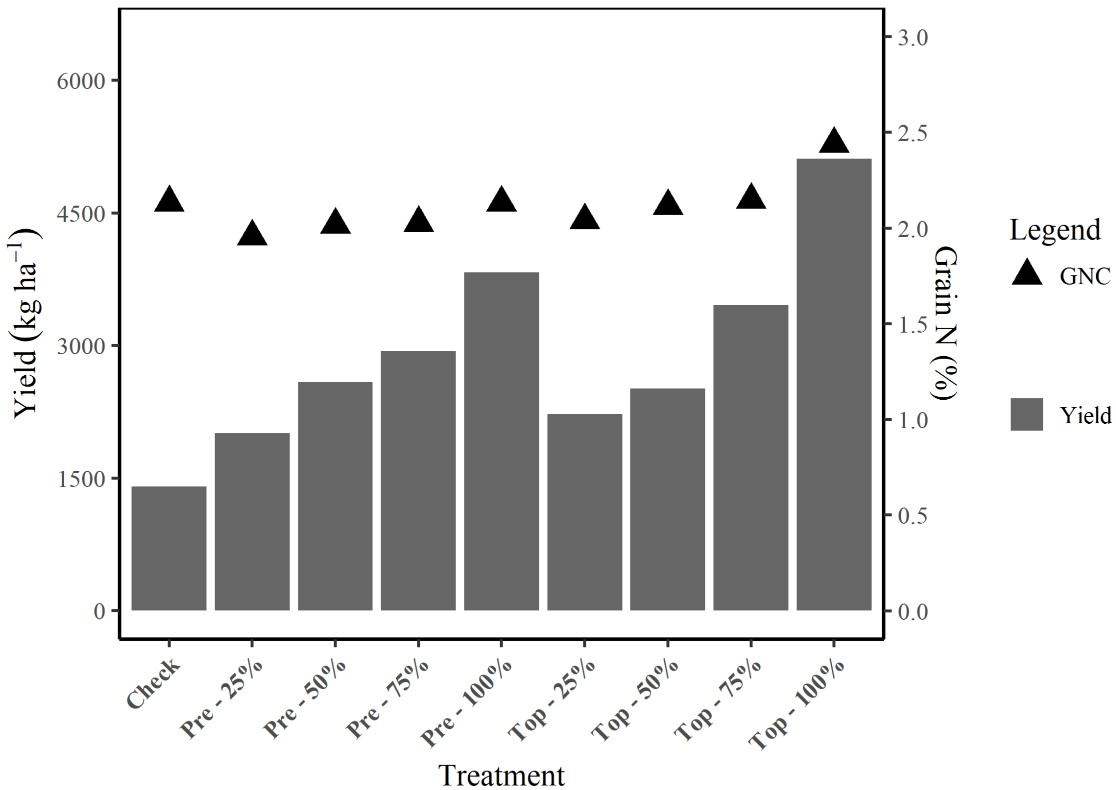


Figure 60 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Ballagh location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

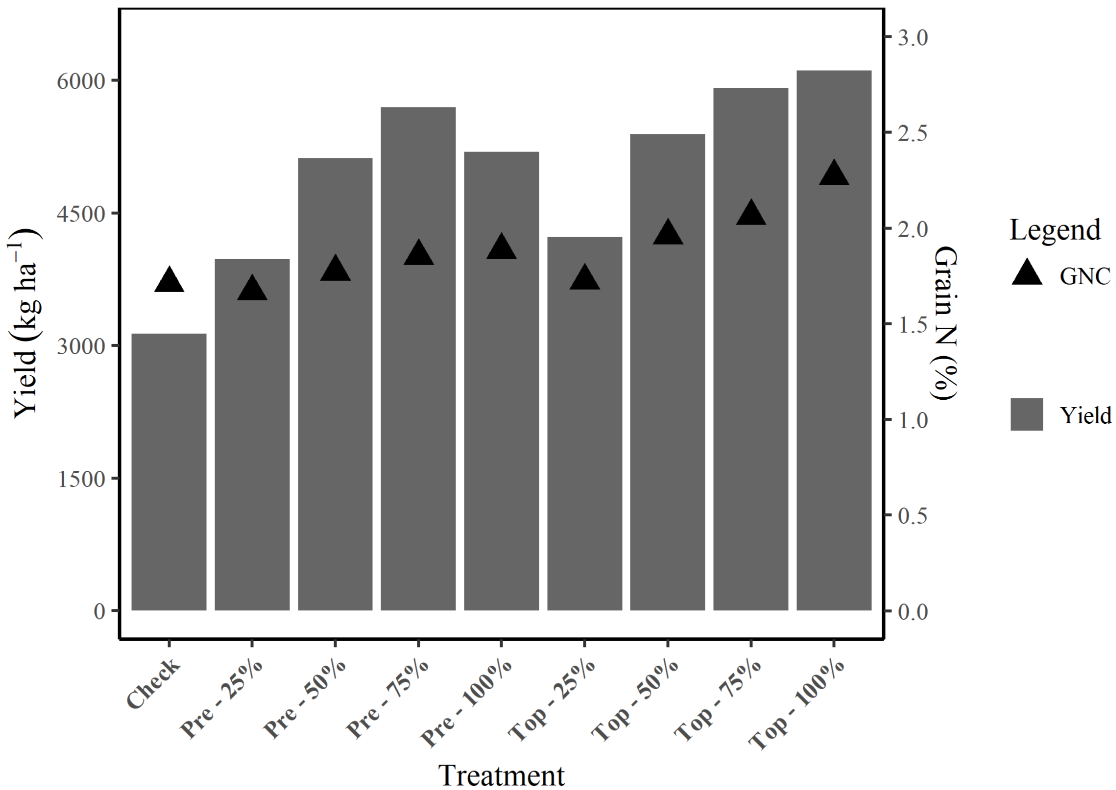


Figure 61 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Byron 2 location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

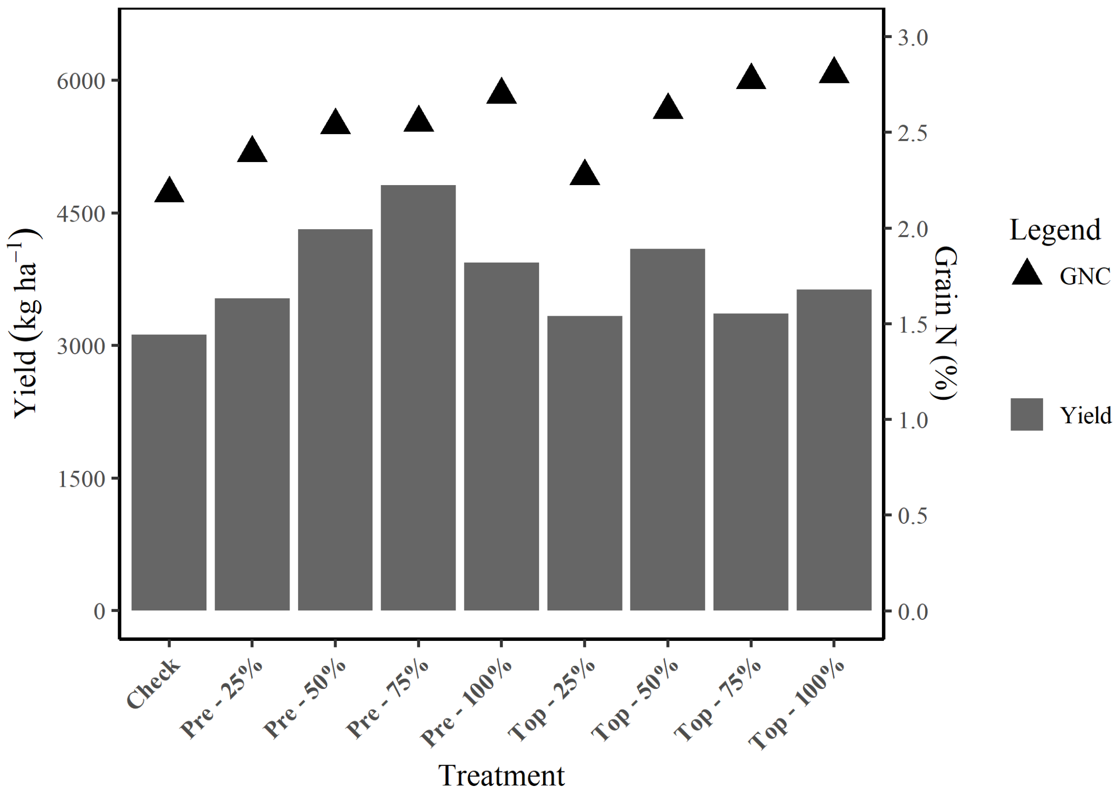


Figure 62 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Byron 3 location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

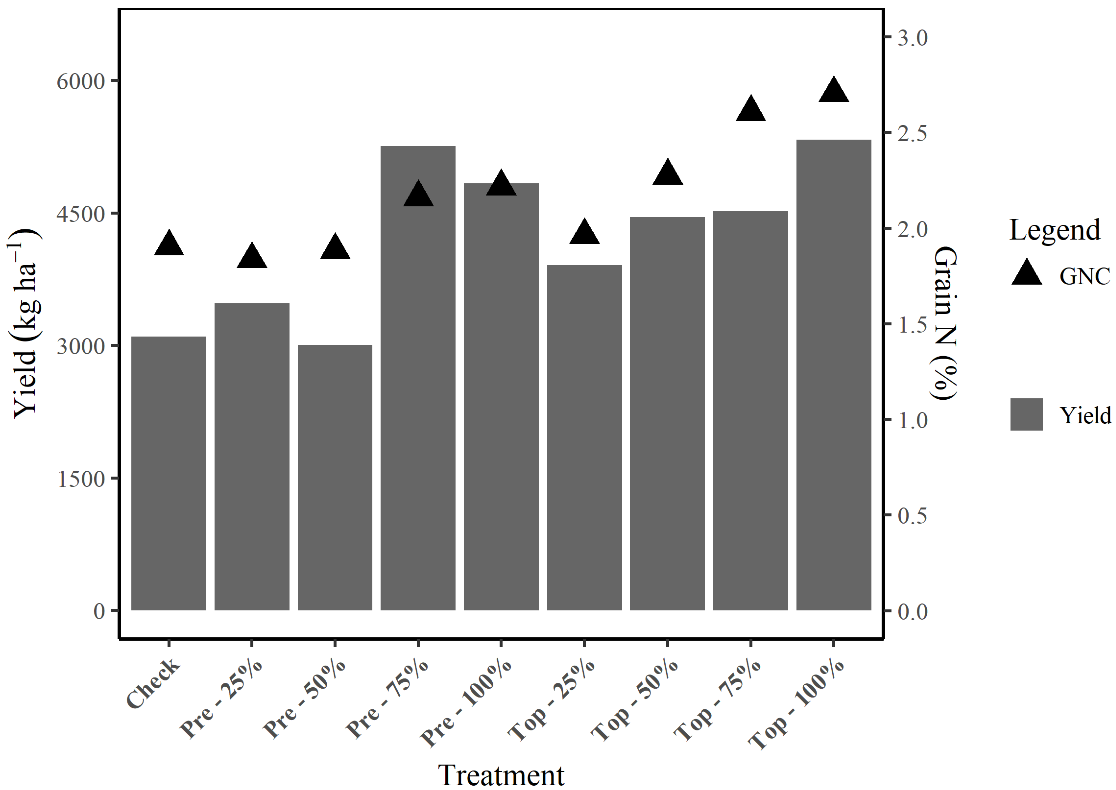


Figure 63 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Carmen location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

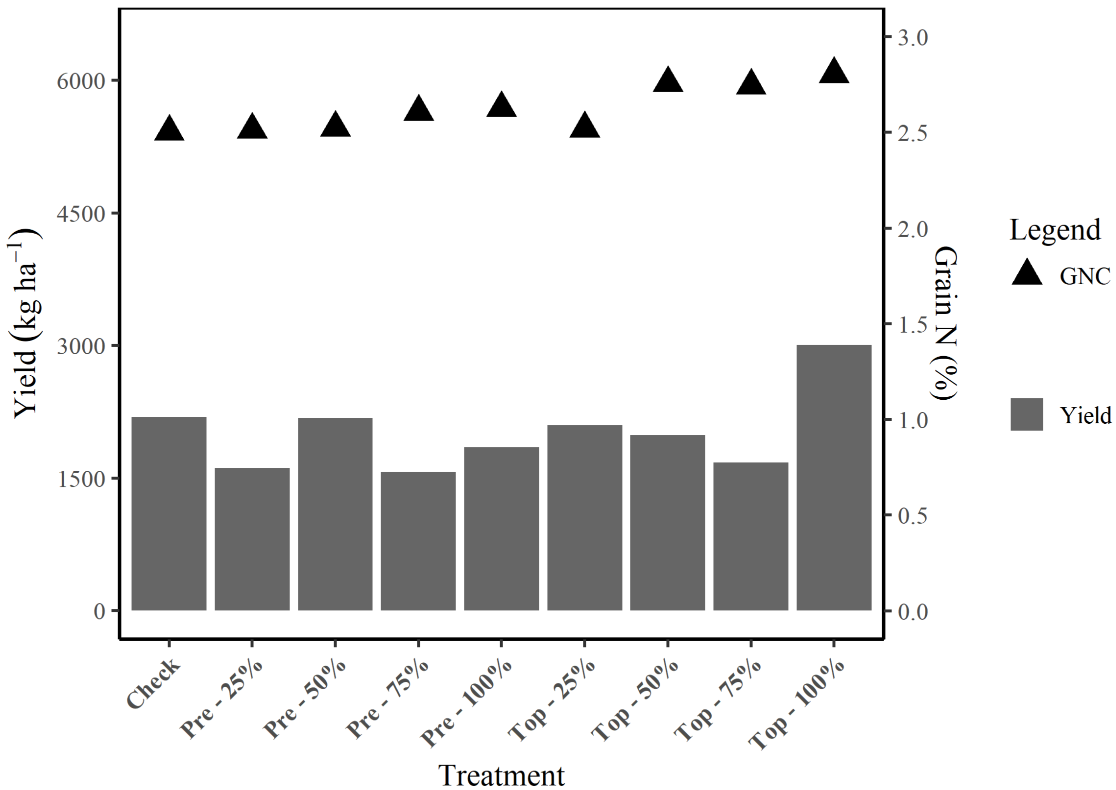


Figure 64 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Chickasha 2 location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

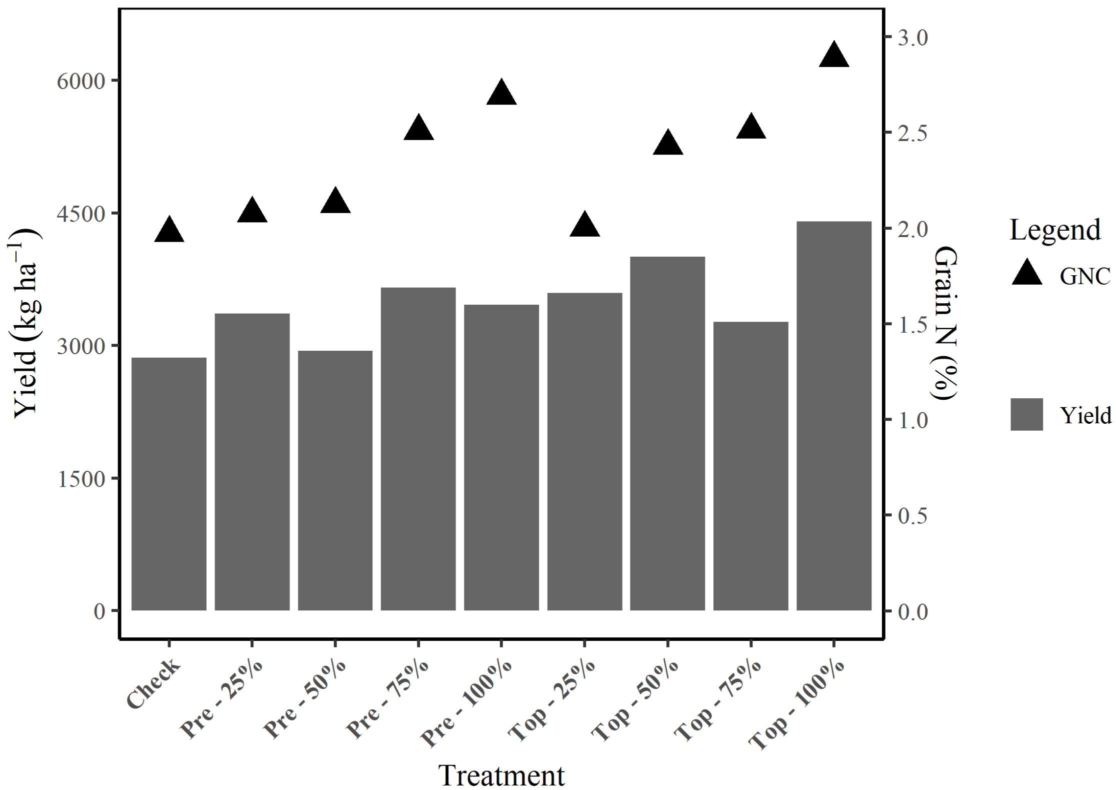


Figure 65 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Dove location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

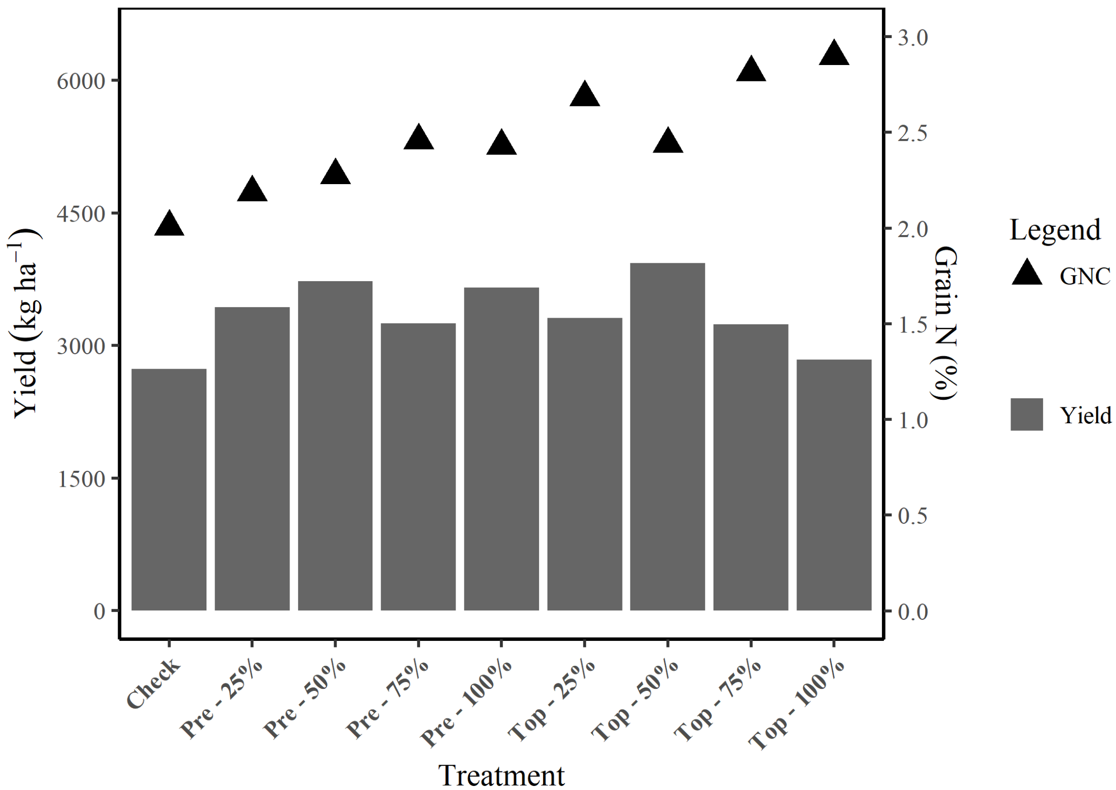


Figure 66 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the El Reno location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

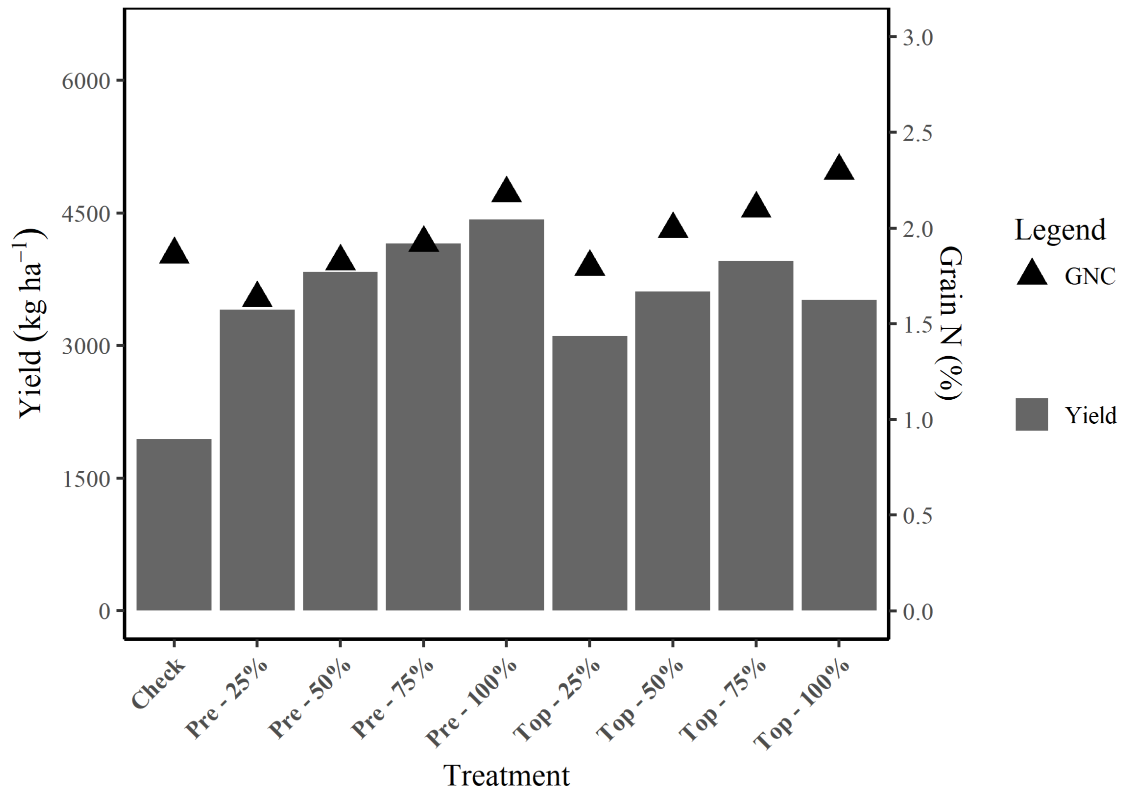


Figure 67 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Elmwood location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

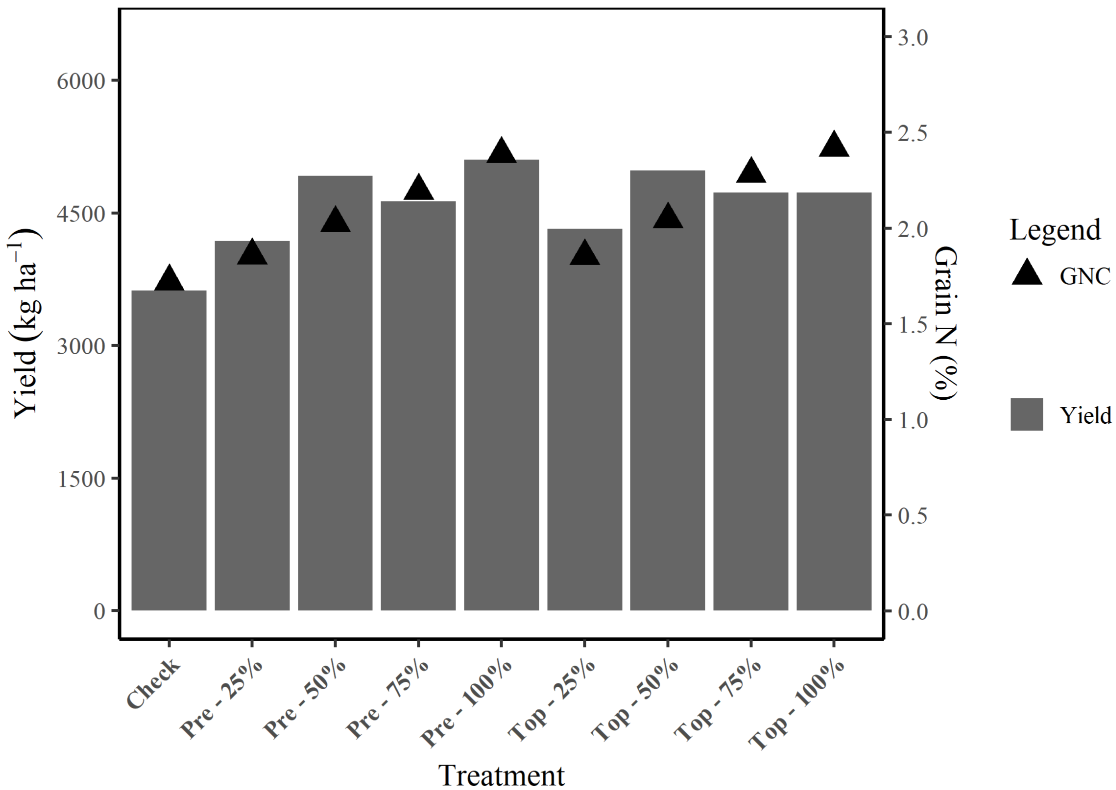


Figure 68 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Granite location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

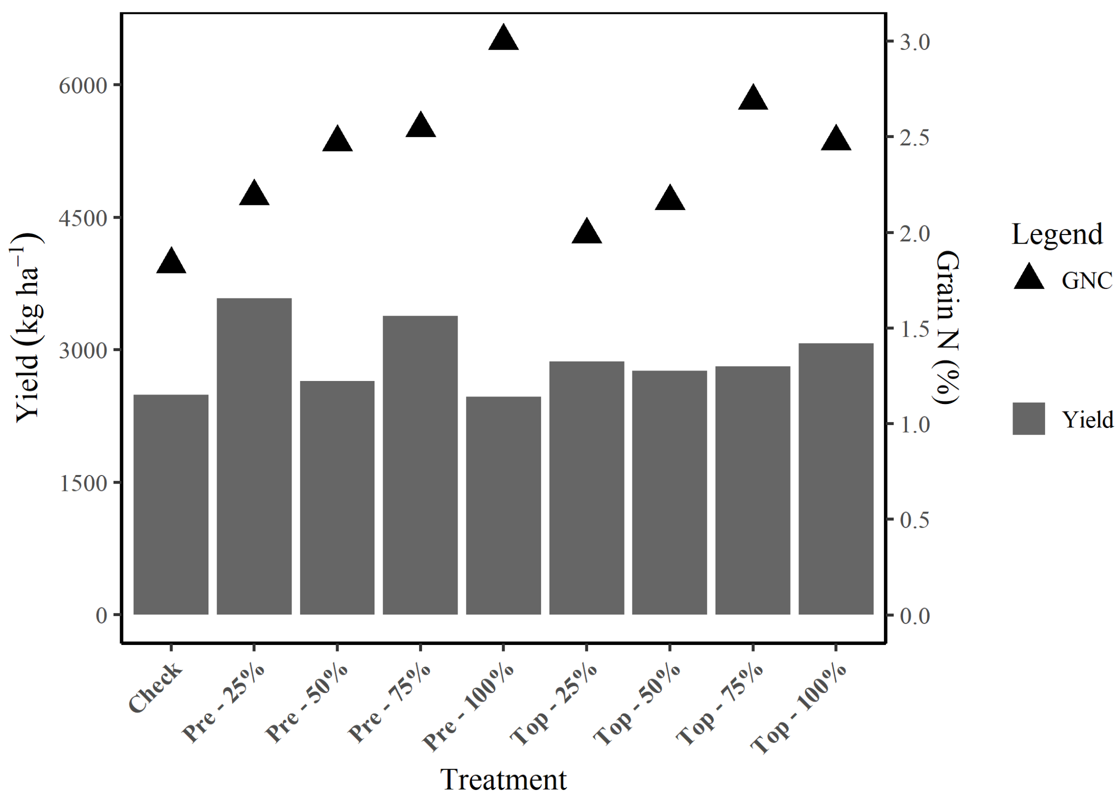


Figure 69 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Hobart location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

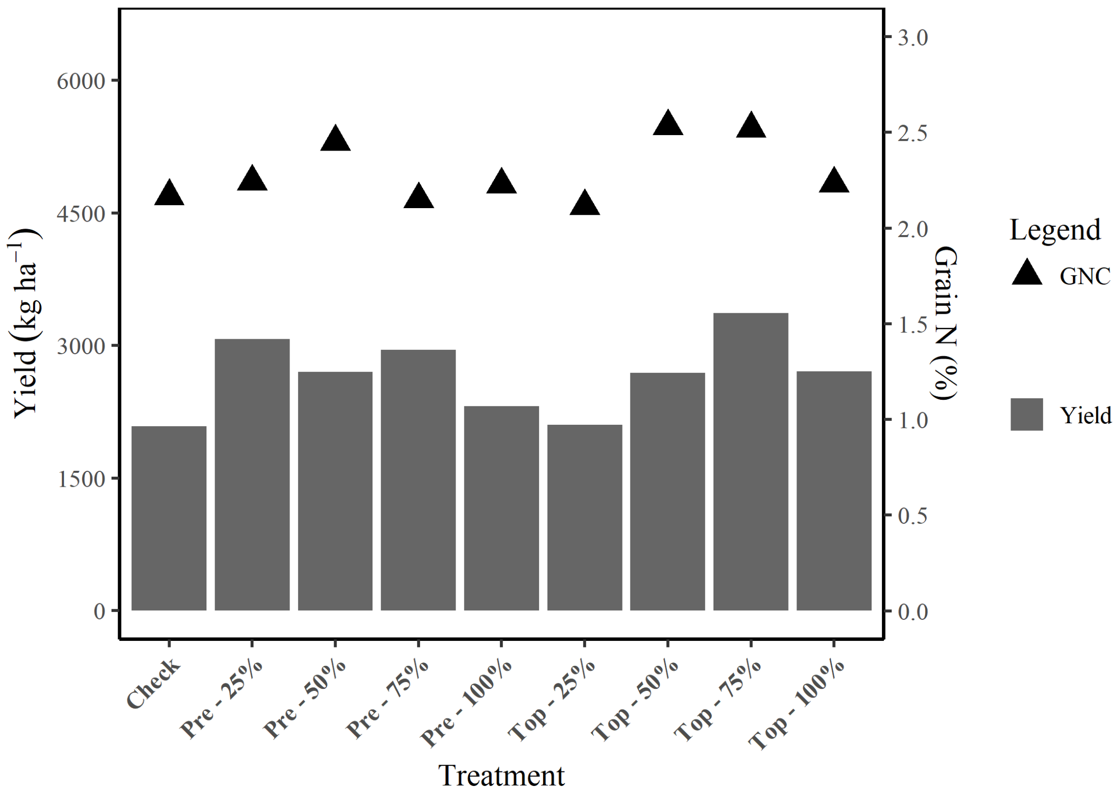


Figure 70 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Lahoma 2 location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

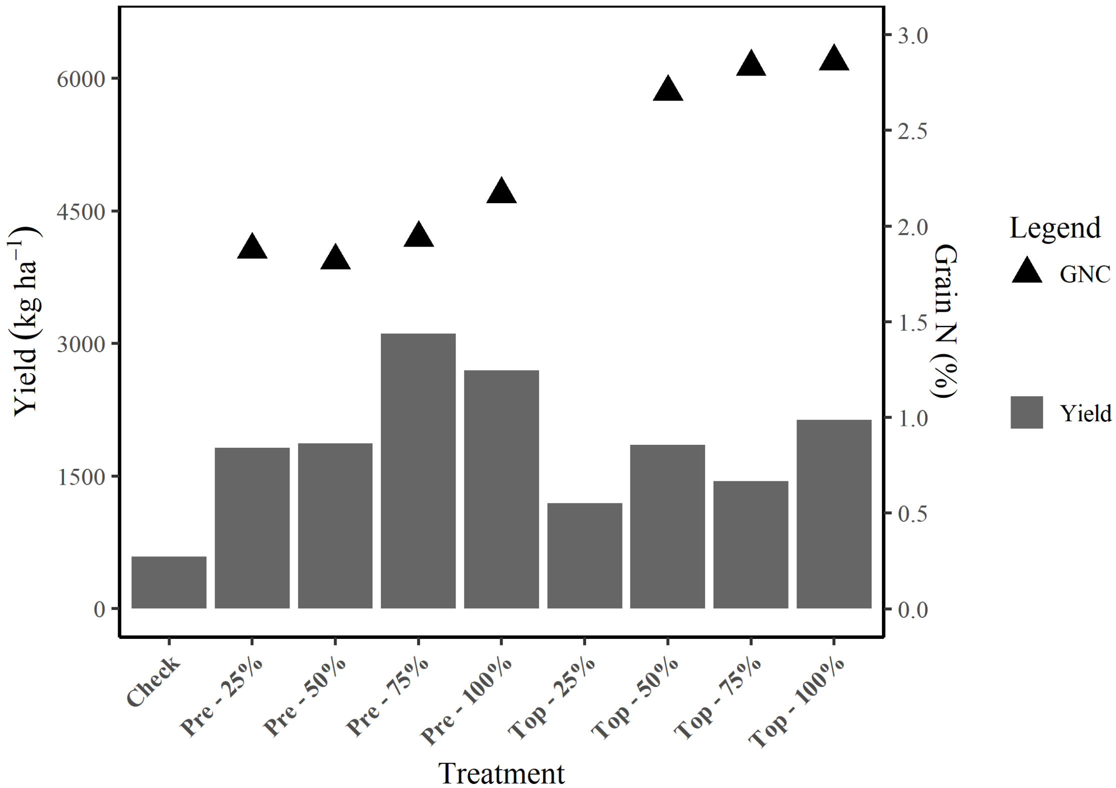


Figure 71 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the LCB location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

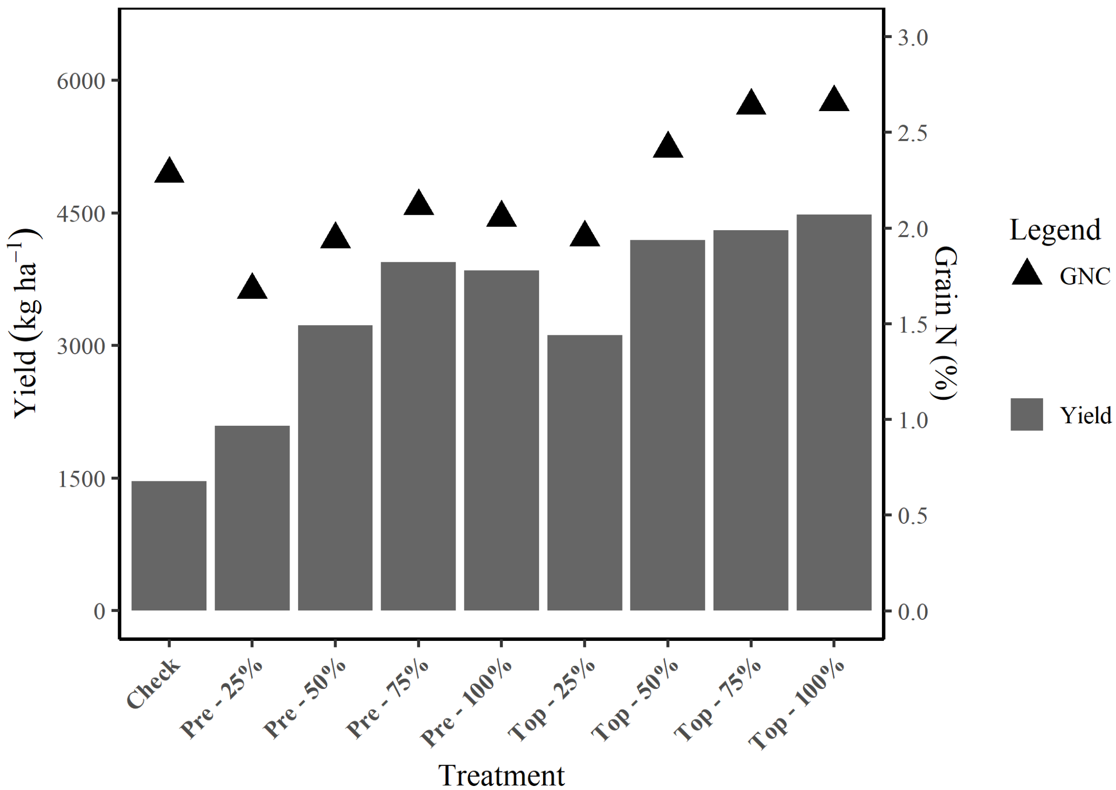


Figure 72 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Nardin location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.

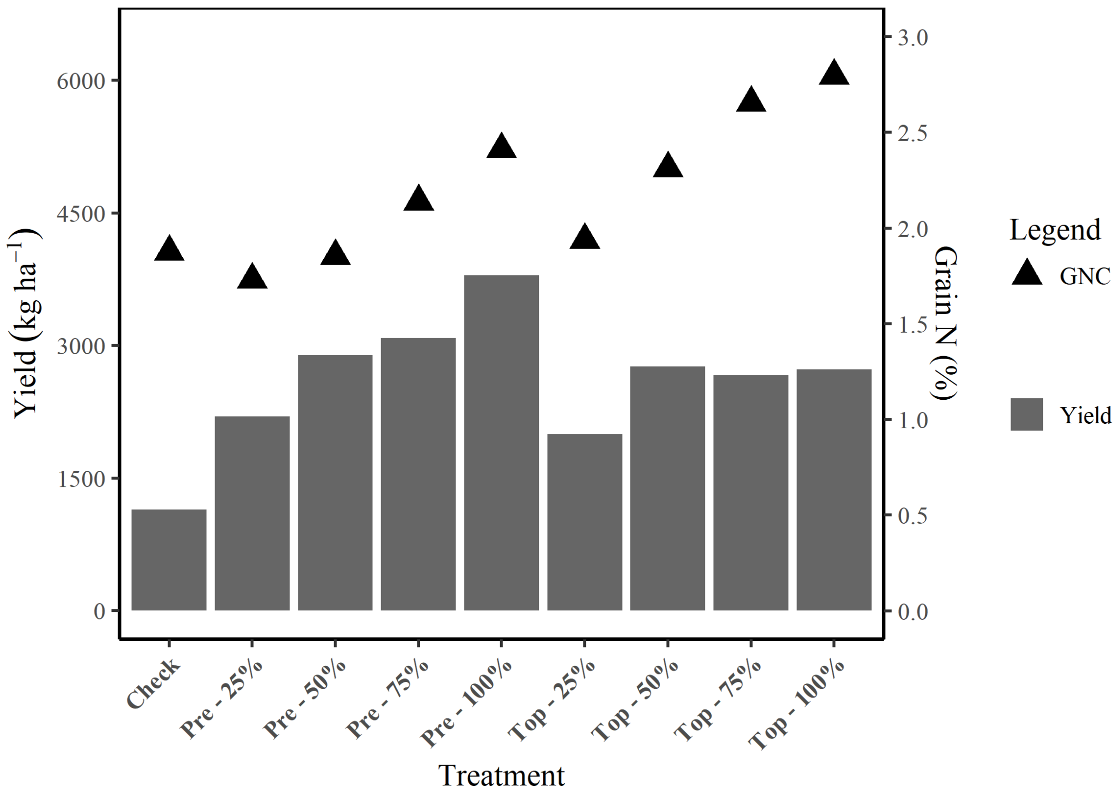
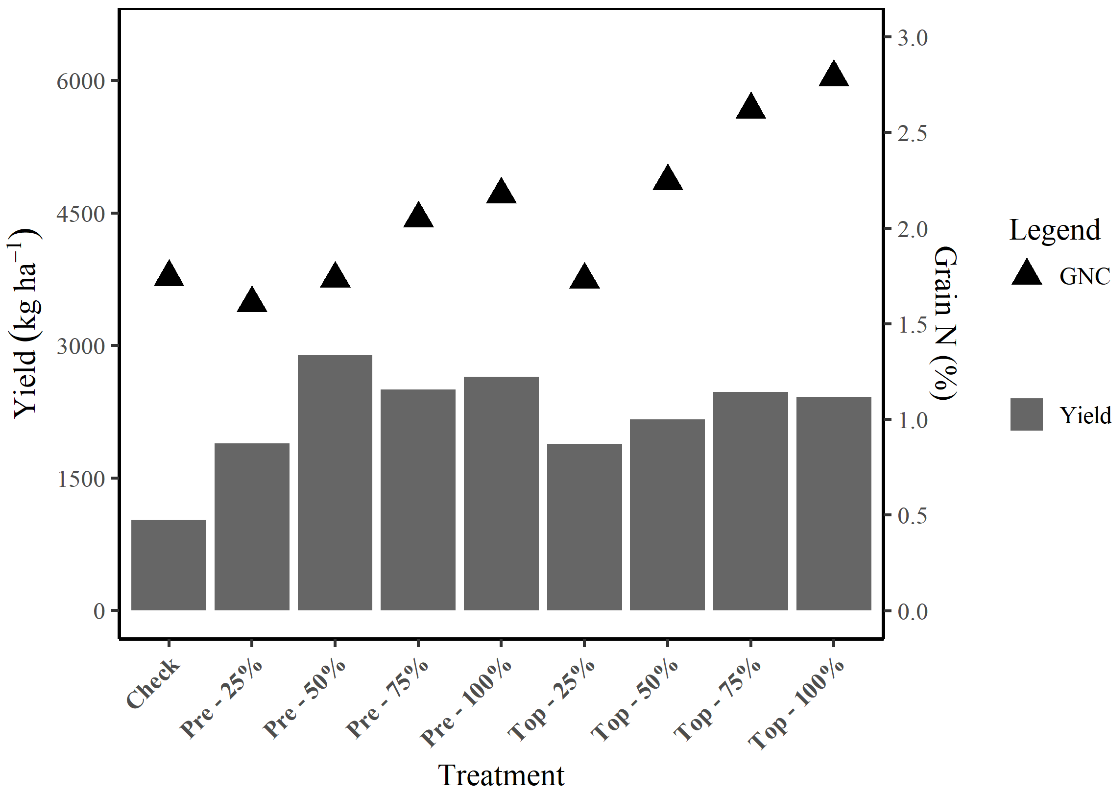


Figure 73 Yield (kg ha^{-1}) and Grain N Concentration (GNC %) for the Tipton location for each treatment. 'Pre' denotes pre-plant application. 'Top' denotes top-dress application. Rate percentage was determined using yield potential of the area, considering the productivity of the location, environment parameters, and historical yield.



VITA

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