Seasonal Changes in Estimated Nitrogen Response in Winter Wheat (Triticum aestivum L.)

By

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Abstract: In 2014 246,618,023 ha of wheat was harvested around the world where wheat made up roughly 8% of land area where crop cultivation is possible. Nitrogen use efficiency (NUE) for cereal crop production is near 33% which can be improved to help with production costs and to diminish potential offsite losses of nitrogen (N) fertilizer. The objective of this work was to use sequential NDVI measurements from two long-term nutrient management experiments to illustrate growth changes over the life cycle with NDVI, known to be a good indicator of total plant biomass. A further evaluation of the response index (RI) of N over one cropping cycle in winter wheat was performed. The RI was determined by dividing the NDVI from the high N rate plot by the NDVI from the 0-N check plot (RI_{NDVI}). Sensor NDVI readings were collected weekly for three months. This approach was hoped to expand our knowledge of mapping wheat growth stages using sequential NDVI data. Definitive differences in RI_{NDVI} were observed over time, and that peaked for Experiment 222, but less so for Experiment 502 where at lower N rates (< = 90 kg N ha-1); this peak tended to occur, when 120 days from planting to sensing, where growth was possible, had occurred. For Experiment 502, declining slopes for RI's over time, computed with lower N rates, suggests that N in the soil system was being depleted and that the rates were clearly not sufficient to provide for plant demand for N mid to later season. Compared to results of past studies the maximum NDVI's collected were lower, which could be due to a poor plant stand or planting.

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CHAPTER I

Introduction

As the world population rises the need for food increases as well as the need for efficient use of nutrients that are applied. Nitrogen (N) is one of the most important nutrients applied for crop production and that is costly for producers. When mismanaged N can be lost and have a negative environmental impact. Current estimates of N use efficiency (NUE) for cereal crop production in the world are near 33% (Raun and Johnson, 1999) indicating that much of the applied fertilizer N is not utilized by the plant and is susceptible to loss from the soil-plant system. Supplying fertilizer N only when crop response is expected may improve use efficiency and profitability (Mullen et al., 2003). The correction of this nutrient use inefficiency has been recognized by many organizations and areas of the world. Oklahoma State University is one of those organizations, and since 1991 the Departments of Plant and Soil Sciences (PSS) and Biosystems Agricultural Engineering (BAE) have worked together to develop technologies to help producers better manage N fertilizer, and to achieve maximum production with minimal inputs (Rutto and Arnall, 2009).

An important crop that requires N applications is wheat (Triticum aestivium L.). This cereal crop provides >60% of the calories and protein for our daily life (Gill, B.S. et al., 2004).

Currently there are 14.76 billion ha (36.48 billion acres) of land that exists globally, out of that land 3.1 billion ha (7.68 billion acres) or 21% of the total land area is cultivable land (Nahar, K., 2011). In 2014, 246,618,023 ha of wheat was harvested around the world (FAOSTAT, 2014) where wheat made up roughly 8% of land area, where crop cultivation was possible. In the United States the production value of wheat was $10,203,360,000 in 2015, making it the third highest value for grains and hay crops, with the first being corn ($49,038,819,000) and the second being hay,($16,839,538,000) (USDA, 2016). As a result of wheats importance as a food grain and the current low NUE it is important that continued effort be made in improving nitrogen management.

For detecting the biomass one must first consider that plants can display whether they need nutrients through the presence of chlorophyll a and b, which provide an indication of the physiological status of the plant (Jones et al., 2007). The presence of available N in soils and chlorophyll in plants are directly related; thus chlorophyll may be used as an indirect indicator of N levels in fertilizer management systems (Jones et al., 2007). The technology that is being utilized in this study and is also used to help producers manage N applications is the GreenSeeker™ (Trimble Navigation Co., Trimble.com) sensor, which is a device used to estimate plant biomass using indirect sensor measurements, specifically NDVI or the normalized difference vegetation index. This spectral index, NDVI, is a measure of the red and near infrared regions on the electromagnetic spectrum. Near infrared (NIR) diffuse reflectance spectrophotometry has been used to measure protein, moisture, fat and oil in agricultural products (Wetzel, 1983). The NIR spectral region has also been used for predicting organic C and total N in soils (Dalal and Henry, 1986; Sudduth, 1991). Because of this, NDVI is a good measure of agronomic and biophysical plant parameters and it is also closely related to plant productivity. Present "GreenSeeker™ technology measures NDVI by using a self-illuminated (active sensor) light source (Crain et al., 2012), which directs visible (VIS) red light (660 nm) as well as near infrared light (770 nm) at the plant canopy of interest" (Dunn et al., 2015). The equation for NDVI as reported by Solie et al. (2012) is:

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$$

Where ρ_{NIR} and ρ_{RED} are the reflectance values in the near infrared (780-880) and red (650-670) wavelengths, respectively.

Several authors have proposed that the RI can predict actual crop response to applied N thus improving NUE in cereal production within a given year (Johnson and Raun, 2003; Raun et al., 2002). Nitrogen use efficiency of winter wheat was improved by more than 15% when N rate recommendations were based on mid-season predictions of yield potential (YP0) and response index compared to conventional N rate recommendations (Raun et al., 2002). Values for $RI_{Harvest}$ were calculated using the following equation (Mullen et al., 2003):

$$RI_{Harvest} = \frac{Mean\ Yield\ Highest\ N\ Treatment}{Mean\ Yield\ of\ the\ Check\ Treatment}$$

Similarly, crop N response can be estimated by RI_{NDVI} using the equation (Mullen et al., 2003):

$$RI_{NDVI} = \frac{NDVI\ from\ the\ High\ N\ Treatment}{NDVI\ from\ N\ Check\ Treatment}$$

In an article by Chung et al. (2010), the RI estimated in-season (RI_{NDVI}) was used to predict the RI at harvest ($RI_{Harvest}$) at Feekes (Large, 1954) physiological growth stages 5 (leaf sheaths strongly erect), 9 (ligule of flag leaf visible), and 10.5 (heading complete). It is important to note that using NDVI information over a range of plant growth stages is not a new idea and it is one that has been studied extensively by various authors (Stone et al., 1996; Sembiring et al., 1998).

Like all living organisms, wheat goes through stages as it matures and there are at least five scales commonly used worldwide to describe stages of growth in wheat and other small grains (Miller, 1999). The scale that is most widely used in the United States is the Feekes scale and that partitions whole growth into 11 stages. The growth stages that are commonly evaluated for NDVI include Feekes growth stages 3, 5, 6, 7 and 10 (Large, 1954). Feekes 3 is when the tillers are formed. Most of the tillers that contribute to grain yield potential are completed during this stage and leaves begin to twist spirally (Miller, 1999). Feekes 5 is when the leaf sheaths are strongly erect, and many varieties of winter wheat which are creeping or low growing, grow vertically at this stage (Miller, 1999). Feekes growth stage 6 is when vernalization is required in winter wheat prior to spikelet differentiation. Prior to Feekes 6 the nodes are all formed, but are sandwiched together so that they are not readily distinguishable to the naked eye. At this stage, the first node is swollen and appears above the soil surface (Miller, 1999). The second to last stage that is being evaluated is Feekes 7 or "jointing" which is when the "second node of the stem is formed, next to last leaf just visible (Large, 1954). Finally the last stage that was included is Feekes 10 which is when the head is fully developed and can be easily seen and this is then divided into several added steps (Miller, 1999).

Many other researchers have noted which growth stages are the most crucial for NDVI data collection including Feekes growth stage 5 (pseudo-stem, formed by sheaths of leaves strongly erect), 9 (ligule of last leaf just visible), 10.5 (flowering), and 11.2 (mealy ripe, contents of kernel soft but dry) (Large, 1954). Similar work was reported by Sembiring et al. (2000) on sensor data at Feekes growth stages 5 and 7. Results from this study**)** "TotalNuptake in winter wheat at Feekes growth stages 4, 5, 7, and 8 was highly correlated with NDVI. The amount of variability in total N uptake as explained by NDVI increased with advancing growth stage (Feekes 4 to 7), largely due to an increased percentage of soil covered by vegetation" (Sembiring et al. 2000). Even in other countries such as Pakistan, defining when the appropriate time to sense wheat, remains important. The milky-grain stage (Feekes equivalent is 10.5) (Simmons et al., 1985) is the best depictive stage for recording NDVI as it can be correlated with grain yield, better so than earlier measurements for the results of the study, "the results suggested that nitrogen treatment N4 (220 kg ha−1) and cultivar Faisalabad-2008 gave maximum NDVI value (0.85) at grain filling stage among all treatments" (Sultana et al., 2014). There are many different ideas of when the best time to take NDVI data on wheat for yield prediction and these have been tested by many researchers.

Past studies use satellite data, or have minimal variations of time of sensing, so there has not been a comprehensive evaluation of wheat as it grows according to NDVI using a greenseeker device. This growth tracking of wheat was considered useful because it has the potential to allow researchers and producers to better predict when to sense their crops so that the optimal amount of N can be applied. Previous research involving NDVI and the growth of wheat include many studies, and one is the examination of seasonal growth profiles developed from AVHRR-NDVI data to estimate wheat yields where the results stated that NDVI seasonal growth profiles can provide good estimates of regional and farmscale yield at the end of the growing season and during the later part of the growing season, prior to harvest, at the regional scale. That same study had results that stated, Early-season NDVI parameters provided poor estimates of yield, limiting our ability to provide yield estimates early in the growing season when some farm management decisions need to be addressed. However, early-season farm monitoring with weekly updated NDVI imagery could provide crop yield estimation when little other data is available to land managers for yield estimation." (Labus et al., 2010).

In a different study, (Moriondo et al., 2007) tested the methodological framework that employed NDVI data taken from satellite platforms and a simulation model (CROPSYST) to estimate wheat yield. Two Italian provinces where wheat is widely grown were accessed in this study and the results were that "Wheat NDVI reached a maximum of 0.73 at the end of April (12th 10-day period) at Grosseto, while it reached a maximum of 0.80 at the beginning of April (10th 10-day period) at Foggia" (Moriondo et al, 2007)

Another example of an international study is from China, it had an objective to create a "Crop Proportion Phenology Index (CPPI) to express the quantitative relationship between the MODIS vegetation index (VI) time series and winter wheat crop area" (Pan et al., 2012). Further work that estimated wheat yield using satellite data was from (Ren et al., 2008) and it was done "to test the suitability of the method, depending on predicted crop production, to estimate crop yield with a MODIS-NDVI- based model on a regional scale" (Ren et al., 2008). This paper also uses MODIS-NDVI data to estimate the winter wheat yield. There is even a study from Lamb et al. (2011) that compared data that was retrieved from the air using a device called an “aerial Raptor ACS-225LR” to data that was taken from the ground using a “CropCircle ACS-210” which is a ground sensor that was attached to a motor bike to acquire data. Though this study used a ground sensor it did not use the ground sensor to evaluate the wheat plants; the results of the study involved “Comparisons of Raptor-derived NDVI maps with that produced by with a detailed on-ground NDVI survey indicated the aerial sensor values were highly correlated with close to unity slope and zero offset. By way of example, a desktop calculation demonstrated that the observed deviation between aerial and on-ground NDVI values were small enough to have no significant impact on two published algorithms for using NDVI to estimating pasture biomass and forecasting wheat yield.” (Lamb et al, 2011)

. While there are many other examples of using NDVI data from wheat, one has yet to find an evaluation of the seasonal changes of the growth of wheat using the Greenseeker device. Most of the studies are done for a region or a very large area of wheat where this study deals with a much smaller area of land than other related studies. Having the information about the seasonal growth changes in wheat through NDVI data is important because it could serve as a valuable reference point for producers and researchers so they can compare the growth of wheat at any stage. The objective of this work was to use sequential NDVI measurements from two long-term nutrient management experiments to illustrate the change in response index over time in wheat production environments.

CHAPTER II

Methods

Two long-term experiments at Oklahoma State University, Experiment 222 (Kirkland, silt loam, fine, mixed, thermic, Undertic Paleustoll) and Experiment 502 (Grant silt loam, fine-silty, mixed, thermic Udic Argiustoll) were targeted for composite in-season NDVI sampling. Experiment 222 was established in the fall of 1968, and harvested for the first time in the spring of 1969. Experiment 222 is located at the Agronomy Research Station in Stillwater, Oklahoma. This trial was established to evaluate long-term winter wheat grain yield response to applied N, phosphorus (P) and potassium (K). Applications of sulfur (S) and magnesium (Mg) were also compared. A tendency for increased yields with applied P and K was present for the 1989-1998 time period, but, this was not significant. Over the 47 years that these treatments have been evaluated, only applied N has produced a significant increase in grain yields. In the fall of 1970, experiment 502 was established near Lahoma, OK, to examine the effects of annual application of N, P, and K on wheat yields (Claborn, 1996). In the first ten years of Experiment 502, grain yields increased by an average of 952 kg ha^{-1} when 90 kg ha^{-1} as ammonium nitrate was applied preplant. Limited response to applied P and K has been seen in any year. Soil test P and K levels at the start of this experiment were near 100% sufficiency.

Begin Soil test P levels have declined somewhat where no P has been applied; however, sufficiency levels still exceed 100%. Soil organic carbon (C) levels have increased with increasing N applied when compared to the check. In each plot, grain was subsampled for total N analysis (Schepers et al., 1989).

Long term Experiment 222 and Experiment 502 were used for estimating the in-season response index based on differences coming from a non-N-limiting area and a check (0 N). A randomized complete block design was used at both sites with 4 replications. Not all treatments from each of these trials were used as they evaluate different parameters. Four of thirteen and five of fourteen total treatments from Experiment 222 and Experiment 502, respectively were selected for extensive NDVI sampling (Tables 1 and 2, Figures 1 and 2). Tables 1 and 2 include treatments and rates of fertilization for Experiment 222, and Experiment 502, respectively. Soil testing results from each site are reported in Table 3. Plot plans for both locations are also included in Figures 1 and 2. Sensor NDVI readings were collected weekly from both locations over a three month period during the growth cycle of winter wheat. At harvest, grain yields were obtained using a self-propelled Kincaid 8XP combine, by harvesting the center 2 m of each plot. In addition each plot was subsampled for total N analysis from grain samples (Schepers et al., 1989). An RI based on NDVI was determined by taking sensor readings in the non-N-limiting plots and dividing by the check treatment (0 N). For Experiment 222 treatments 1, 2, 3, and 4 were used. Treatment 1 has received no N, but has received fixed rates of P and K that match up with treatments 2, 3, and 4. (Table 1, Figure 1).

For Experiment 502 treatments 2, 3, 4, 5, 6, and 7 were used. Treatment 2 received applied P and K, but no N. Treatments 3, 4, 5, and 6 received 23, 45, 68, 90 kg

ha^{-1} N as urea (46% N), respectively. Treatment 7 received 112 kg ha^{-1} N applied annually. Phosphorus was applied pre plant and incorporated as triple super phosphate (20% P), and K applied as potassium chloride (49% K) at both locations. Experiment 222 was planted on October 12th 2015, and Experiment 502 was planted on October 20th 2015.

Depending on weather conditions the original goal was to take NDVI readings at both locations once a week until the wheat entered the flag leaf stage. Ten separate readings were collected at each location. After the readings were taken, NDVI values across replications were averaged by treatment; then using the averaged NDVI values the RI's were calculated by dividing the NDVI of the treatment receiving N by the NDVI of the treatment that did not receive N fertilizer. Those RI values were recorded and transcribed so as to compute RI based on the number of days after planting. The graphs were interpreted and described according to variations in NDVI and RI values.

CHAPTER III

Findings

The NDVI values collected are shown in Tables 4 and 5 from Experiment 222 and Experiment 502, respectively. The NDVI values are also displayed in Figures 3 and 4. The response indexes for Experiment 222 and Experiment 502 are shown in Figures 5 and 6, respectively.

In Figure 3 (and Table 4) the NDVI values from the treatment with 0 kg ha^{-1} N, begin just below 0.6 and then decline to almost 0.3. In the treatment with 45 kg N ha^{-1}, NDVI values remain between 0.5 and 0.6 until 152 growing degree days when the NDVI values then drop to slightly above 0.4 and then below 0.38. The treatment receiving 90 kg N ha^{-1} begins closer to 0.5 and follows a similar trend as the treatment receiving 0 kg N ha^{-1} and the treatment receiving 45 kg N ha^{-1} but the first value for treatment with 135 kg N ha^{-1} is lower than treatment with 0-N and 45 kg N ha^{-1}. The treatment with 90 kg N ha^{-1} had values that remained above 0.5 until growing degree days reached 152 where the NDVI values were below 0.5 and above 0.4. The treatment receiving 135 kg N ha^{-1} N begins slightly above 0.4 and then steadily increases to above 0.6 (actual value 0.628) where the growing degree days >0 was 166.

For Lahoma Exp. 502 NDVI data 2016 from Figure 4 (and Table 5) begins with the treatment with 0 kg N ha^{-1}, where the first NDVI value is near 0.3 and steadily increases until growing degree days reach 127 and values were above 0.6 until the last measurement was taken for that treatment. When 23 kg N ha^{-1} was applied, the NDVI was near 0.3 and then increased until growing degree days reached 127 where the NDVI was over 0.5 and that soon dropped. The treatment with 45 kg N ha^{-1} applied also begins near 0.3 and increases until growing degree days reached 127 where the NDVI values remain above 0.5 with a slight increase at the end. The treatment with 68 kg N ha^{-1}applied begins slightly above 0.3 and then increases up to 0.7 at 127 growing degree days. The last two values drop below 0.7 but were above 0.6. In the treatment with 90 kg N ha^{-1} it begins slightly below 0.3 and then rises to near 0.7 where growing degree days are at 127. The values remain slightly below 0.7 through the end. The treatment with 112 kg ha^{-1} applied begins slightly below 0.3 then steadily increases to below 0.7 at growing degree days 127 (actual value 0.68). Beyond 127 growing degree days, the NDVI values begin to decrease until the last measurement that was slightly below 0.6.

Figure 5 displays the response indexes from Experiment 222. For the RI computed using 45 kg N ha^{-1} as the numerator, RI begins above 0.9 and increases to 1.2 and then gets slightly lower during the last readings but values remain above 1.1. The RI computed using 90 kg N ha^{-1} as the numerator, started at 0.9 and increased to slightly above 1.3 where it remained for the last three readings. The RI using 135 kg N ha^{-1} as the numerator begins slightly above 0.7 and increased steadily until the last three readings where RI values increased to 1.7 for the 8^{th} and 9^{th} readings and then increased to 2.0 for the last reading.

In Figure 6, the RI for Experiment 502 is shown. For RI determined using the 22 kg N ha^{-1} rates as the numerator, RI begins at 1 and then decreases to between 0.9 and 0.8 until the last value where it is increased to slightly above 0.9. For the RI determined using 45 kg N ha^{-1} N rate as the numerator the first value was slightly above 1.1 and then decreased to 0.8. For the second to last and last value, it was between 1.0 and 1.1. The RI computed using 67 kg N ha^{-1} as the numerator, this began above 1 and then remained between 1.0 and 1.1 until the last value where RI was above 1.2. When RI was determined using the 90 kg N ha^{-1} rate, this started above 0.9 and values remained between 1.0 and 1.1 except for the7th and 8th that were below 1.0. The RI computed using 112 kg N ha^{-1} as the numerator, began at 1.0, and then increased to 1.15 where the last value was recorded.

Considering the results from Figure 3, the treatment with 0 N applied had NDVI values that decreased as time went on; the treatment with 45 kg N ha^{-1} and the treatment with 90 kg N ha^{-1} also followed a similar trend as the treatment with 0 N applied but with values progressively higher as N rate was increased. The treatment with 135 kg N ha^{-1} applied for that location did not follow a decreasing trend treatment but it increased with time and had the highest recorded NDVI values for Experiment 222.

In Figure 4 the RI values over treatments did not vary much until 127 GDD>0 , after that time period there was a wider range of NDVI values across treatments, and those treatments ranged between 0.5 and 0.7 for the last four readings. Early stage readings began at 0.3, and then increased to just below 0.6. Depending on treatment, values slightly decreased until the last reading. The treatment that received 68 kg N ha^{-1} had its highest NDVI just below 0.7 for the last four readings. The treatment with 45 kg

N ha^{-1} had the lowest recorded NDVI value for Experiment 502 and the highest value recorded for 45 kg N ha^{-1} applied was 0.6 at about 127 GDD>0. The treatment with 45 kg N ha^{-1} was very similar to the treatment with 23 kg N ha^{-1}. The treatment receiving 68 kg N ha^{-1} had the highest NDVI values with its highest value being 0.7 and then the last value being 0.65. When 90 kg N ha^{-1} and 112 kg ha^{-1} were applied, they followed very similar trends but with values slightly lower than 68 kg N ha^{-1}.

When comparing Figures 3 and 4 it can be concluded that the NDVI values from Experiment 502 had more range than Experiment 222 because for the Experiment 502 the lowest value was 0.39 and the highest value 0.7. At Stillwater (Experiment 222), the lowest value was 0.32 and the highest value is 0.63. But for Experiment 222, NDVI values did not follow similar N treatment trends as was seen at Experiment 502. One difference is when it comes to the treatments that had the highest values for NDVI, at the Stillwater location; the treatment with the highest amount of N applied did have the highest NDVI value. While at Experiment 502 the treatment where 67 kg N ha^{-1} had been applied, was the one that had the highest recorded NDVI value.

In Figure 5 where the response indexes for Experiment 222 are displayed and where the RI's ranged from 0.7 to 1.9. When the treatment where RI was computed using the high N rate the potential response to fertilizer increased as time passed. The other two RI's: (45/0) and (90/0) ranged from 0.9 and 1.4 displaying a slope that was not quite as high as the high N rate RI (135/0).

In Figure 6, Experiment 502 RI's had a slightly different range than Experiment 222. For the treatments that have N rate (22/0) and (45/0) the range was from 1.1 to 0.79

while the other RI's (67/0), (90/0), (112/0) had a range from 0.95 to 1.2. This difference in response was not apparent in Experiment 222 treatments, For this site, as time passed plants response to N applied decreased for the treatments that received the lowest amount of N ((22/0) and (45/0)). For the RI using 67/0, the highest RI was observed, yet it was not the treatment that received the highest amount of N. When comparing the (112/0) RI and the (22/0) RI the difference in slope was notable (0.0013 and -0.0016, respectively)

CHAPTER IV

Discussion

To compare my results with past studies, a past study from Sembiring, et al. (2000) noted that TotalNuptake in winter wheat at Feekes growth stages 4, 5, 7, and 8 was highly correlated with NDVI. The time that my locations were sensed was during the time that the wheat reached Feekes growth stages 4, 5, 6, 7, and 8 so for future experimentation it could be correlated with total nitrogen uptake. A past study from Sultana et al., 2014 had results that suggested that nitrogen treatment (220 kg ha−1) gave maximum NDVI value (0.85) at grain filling stage (Feekes 10.5.4) among all treatments. Which compared to my results the maximum NDVI that I collected was lower for both locations indicating a possible stand issues or planting issues. In a past study that evaluates wheat regions in Italy found that Wheat NDVI reached a maximum of 0.73 at the end of April (12th 10-day period) at Grosseto location, while it reached a maximum of 0.80 at the beginning of April (10th 10-day period) at Foggia location. (Moriondo et al., 2007) Compared to the past studies noted my NDVI values were fairly low for the max value detected, where I noted a max of 0.64 for experiment 222 and 0.70 for Experiment 502. This could be due to a poor plant stand at those that could have been caused by weeds or other environmental variations.

Considering the results from Figures 3 and 4 it shows that the amount of N applied to a production system can impact wheat growth over time, demonstrating the importance of altered N use efficiency in winter wheat over time. Furthermore, this is apparent concerning when this impacts the decision to top dress N, based on cost (Lees, 2000). When one considers the differences in NDVI values when it comes to locations, it can be concluded that the difference in environment must be noted and that this can cause estimates of field calculations to not be valid (Fisher, 1926).

CHAPTER V

Conclusion

The objective was to use sequential NDVI measurements from two long-term nutrient management experiments to illustrate the change in RI over time in wheat production environments. Over one growing season of winter wheat, the NDVI values were recorded once a week for 3 months from two locations in Oklahoma. After the NDVI's were recorded RI's were calculated and then displayed in Figures 5 and 6. For Experiment 222 the NDVI values for the treatments with lower amounts of fertilizer added had decreasing values while the treatment with the most applied had increasing values as time passed. The NDVI's for Experiment 502 had a different trend than was noted for Experiment 222. This observation was that all the treatments increased steadily and then by 127 GDD> 0 the NDVI values began to decrease. Results for Experiment 502 also had higher NDVI values for some of the mid-N rates evaluated. In Figure 5 there was a difference in the slope for trend lines displayed by the varying treatments because the slope for the treatment with the most applied N (slope: 0.011) was higher than other treatments (slope 0.0042) indicating an increase in plant response to N fertilizer as time passed.

In Figure 6 the two treatments that had lower amounts of nitrogen, resulted in negative slopes, as time passed while the rest of the treatments with higher N rates had positive slopes. The negative slopes could demonstrate a negative response to N for the very low amounts applied to the wheat. It is possible that at these low rates, the negative slopes suggest that the soil system was being depleted and that the rates were clearly not sufficient to provide for plant demand mid to later season. This is also plausible considering the RI values were similar for all different computations of RI for the very first reading.

When comparing my results to past studies it can be noted that my NDVI maximum values were lower than those past studies, which could indicate a poor plant stand or planting problems. For future experimentation it would be interesting to continue this study to see how the growth of wheat varies year by year. This would allow for more robust analysis and that encumbered added environments known to influence response. This is precisely where sequential NDVI measurements can be used to evaluate response as a function of time.

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Table 1. Fertilizer application rates for Experiment 222, Stillwater, OK (1969-2015)

Treatment	N	P	K
		(kg ha^{-1})	
1	0	29	37
2	45	29	37
3	90	29	37
4	135*	29	37

*split 135 kg N rate to 67.5 kg in fall and 67.5 kg in spring

P applied as triple super phosphate and K applied as muriate of potash.

Table 2. Fertilizer application rates for Experiment 502, Lahoma, OK (1971-2015)

Treatment	N	P	K
		(kg ha^{-1})	
2	0	19	56
3	23	19	56
4	45	19	56
5	68	19	56
6	90	19	56
7	112	19	56

P applied as triple super phosphate and K applied as muriate of potash.

Table 3. Soil test results before planting in Stillwater #222 and Lahoma #502 2016.

			Soil Test Level			
Experiment	Treatment	pH	P (mg kg^{-1})	K (mg kg^{-1})	Organic C (g kg^{-1})	Total N (g kg^{-1})
222	1	5.50	101.56	240.68	8.71	0.87
	2	5.35	82.00	210.37	9.07	0.92
	3	5.22	74.53	201.76	9.39	0.97
	4	4.90	101.56	197.70	10.25	1.00
502	2	6.25	123.22	498.61	8.00	0.74
	3	6.08	137.74	467.35	8.13	0.83
	4	5.75	80.12	378.97	8.51	0.82
	5	5.86	106.19	414.92	9.29	0.91
	6	5.52	92.95	475.06	8.71	0.91
	7	5.52	126.97	487.88	8.81	0.89

pH, 1:1 soil:water, K and P, Mehlich III, organic carbon (C) and total N, dry combustion

Table 4. Sequential NDVI measurements for Experiment 222 and Experiment 502, 2015-2016 growing season.

Exp	Trt (N kg ha^{-1})	12/23/2015 GDD>72 NDVI	1/28/2016 GDD>96 NDVI	2/4/2016 GDD>0 103 NDVI	2/11/2016 GDD>110 NDVI	2/18/2016 GDD>0 117 NDVI	2/25/2016 GDD>0 152 NDVI	3/3/2016 GDD>0 131 NDVI	3/24/2016 GDD>0 152 NDVI	3/31/2016 GDD>0 159 NDVI	4/7/2016 GDD>0 166 NDVI
222	1 (0)	0.58	0.54	0.56	0.49	0.49	0.47	0.49	0.36	0.37	0.32
	2 (0)	0.55	0.59	0.60	0.53	0.54	0.57	0.57	0.44	0.45	0.38
	3 (36)	0.52	0.57	0.60	0.55	0.56	0.59	0.58	0.48	0.50	0.43
	4 (135)	0.44	0.48	0.54	0.49	0.51	0.54	0.56	0.60	0.59	0.63
		12/21/2015 GDD>0 58 NDVI	2/2/2016 GDD>85 NDVI	2/9/2016 GDD>92 NDVI	2/18/2016 GDD>0 101 NDVI	2/23/2016 GDD>0 106 NDVI	3/1/2016 GDD>0 113 NDVI	3/15/2016 GDD>0 127 NDVI	3/22/2016 GDD>0 134 NDVI	3/29/2016 GDD>0 141 NDVI	4/12/2016 GDD>0 155 NDVI
502	2 (0)	0.31	0.32	0.36	0.35	0.46	0.49	0.67	0.67	0.67	0.54
	3 (22)	0.31	0.31	0.36	0.38	0.45	0.48	0.60	0.57	0.55	0.49
	4 (45)	0.34	0.31	0.35	0.41	0.42	0.44	0.58	0.54	0.52	0.56
	5 (67)	0.32	0.32	0.38	0.41	0.50	0.52	0.70	0.70	0.69	0.65
	6 (90)	0.29	0.34	0.38	0.41	0.49	0.53	0.66	0.66	0.65	0.58
	7 (112)	0.29	0.35	0.39	0.42	0.48	0.52	0.68	0.66	0.65	0.60

VI – normalized difference vegetation index

GDD>0, number of days from planting to sensing where growth was possible, using a 4.4C degree threshold

WHEAT FERTILITY EXPERIMENT NO.222

Agronomy Research Station

Established 1969

Location: **Stillwater**

Plot size: 20' x 60'
Alley: 17'

Total Trial Area:
137' x 520'

OBJECTIVE: To study fertilizer nitrogen, phosphorus, and potassium in winter wheat. In recent years, this study has also been used to develop yield potential models and yield predictions through sensor based technologies.

TRT	Pre-plant N rate (kg N / ha)	Pre-plant P rate (kg P / ha)	Pre-plant K rate (kg K / ha)
1.*	0	29	37
2.*	45	29	37
3.*	90	29	37
4.*	135^	29	37
5.	90	0	37
6.	90	15	37
7.	90	44	37
8.	90	29	0
9.	90	29	74
10.*	0	0	0
11.	135 ^	44	74
12.	135 ^	44	0
13.	90	29	37 (Sul-Po-Mag)

N applied as 46-0-0 (Urea)
P applied as 0-46-0 (Triple Super Phosphate)
K applied as 0-0-60 (Potash)
* - YP plot
^ - Split 134 kg/ha N rates to 67 kg/ha N (fall) and 67 kg/ha N (spring)

1, 2 – Harvest Sequence Number

1, 2 – Treatment Number

1 , 2 – Soil Sample Sequence Number

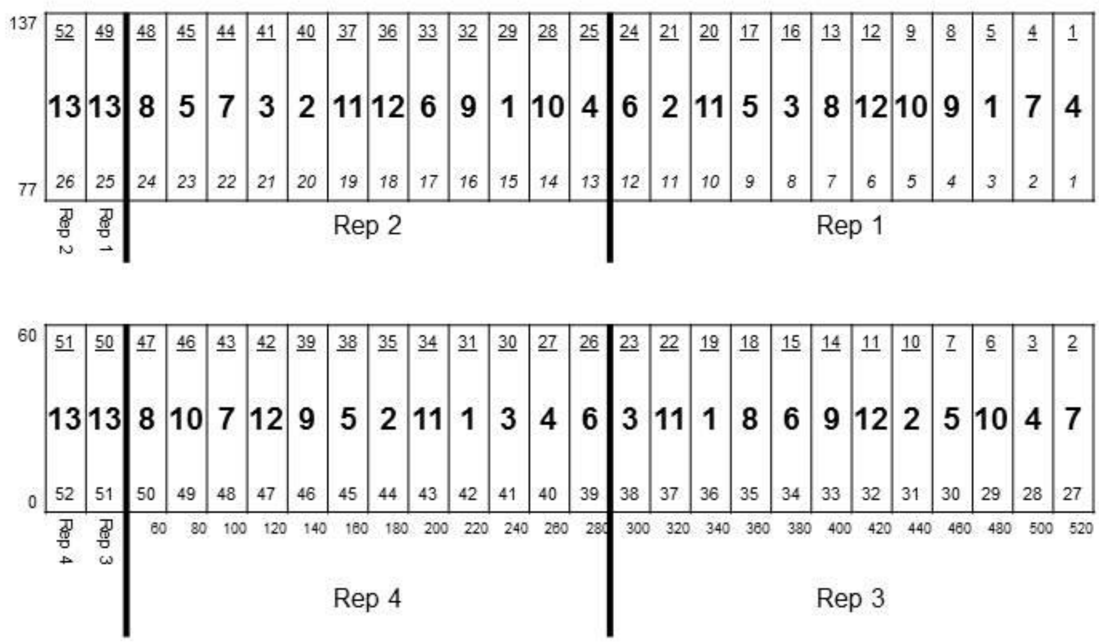

Figure 1. Treatment structure employed and field plot plan for Experiment 222, Stillwater, OK.

WHEAT FERTILITY EXPERIMENT NO.502

North Central Experiment Station

Established 1970

Location: **Lahoma**

Plot size: 16' x 60'
Alley: 20'

Total Trial Area:
224' x 300'

OBJECTIVE: To study fertilizer nitrogen, phosphorus, and potassium in winter wheat. In recent years, this study has also been used to develop yield potential models and yield predictions through sensor based technologies.

TRT	Pre-plant N rate (kg N / ha)	Pre-plant P rate (kg P / ha)	Pre-plant K rate (kg K / ha)
1.*	0	0	0
2.*	0	19	56
3.*	22	19	56
4.*	45	19	56
5.*	67	19	56
6.*	90	19	56
7.*	112	19	56
8.	67	0	56
9.	67	10	56
10.	67	29	56
11.	67	39	56
12.	67	29	0
13.	112	39	56
14.	67	19	56 (Sul-Po-Mag)

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

<u>1</u>, <u>2</u> – Harvest Sequence Number

1, 2 – Treatment Number

1, 2 – Soil Sample Sequence Number

	300	<u>4</u>	<u>5</u>	<u>12</u>	<u>13</u>	<u>20</u>	<u>21</u>	<u>28</u>	<u>29</u>	<u>36</u>	<u>37</u>	<u>44</u>	<u>45</u>	<u>52</u>	<u>53</u>
Rep 4		**3**	**5**	**13**	**6**	**10**	**2**	**4**	**7**	**12**	**1**	**8**	**14**	**9**	**11**
	240	*43*	*44*	*45*	*46*	*47*	*48*	*49*	*50*	*51*	*52*	*53*	*54*	*55*	*56*
	220	<u>3</u>	<u>6</u>	<u>11</u>	<u>14</u>	<u>19</u>	<u>22</u>	<u>27</u>	<u>30</u>	<u>35</u>	<u>38</u>	<u>43</u>	<u>46</u>	<u>51</u>	<u>54</u>
Rep 3		**1**	**14**	**2**	**7**	**11**	**3**	**9**	**12**	**5**	**13**	**4**	**8**	**10**	**6**
	160	*29*	*30*	*31*	*32*	*33*	*34*	*35*	*36*	*37*	*38*	*39*	*40*	*41*	*42*
	140	<u>2</u>	<u>7</u>	<u>10</u>	<u>15</u>	<u>18</u>	<u>23</u>	<u>26</u>	<u>31</u>	<u>34</u>	<u>39</u>	<u>42</u>	<u>47</u>	<u>50</u>	<u>55</u>
Rep 2		**4**	**8**	**3**	**1**	**11**	**13**	**12**	**7**	**14**	**6**	**9**	**10**	**2**	**5**
	80	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*
	60	<u>1</u>	<u>8</u>	<u>9</u>	<u>16</u>	<u>17</u>	<u>24</u>	<u>25</u>	<u>32</u>	<u>33</u>	<u>40</u>	<u>41</u>	<u>48</u>	<u>49</u>	<u>56</u>
Rep 1		**8**	**2**	**4**	**6**	**14**	**9**	**10**	**5**	**7**	**12**	**1**	**3**	**13**	**11**
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
	0	16	32	48	64	80	96	112	128	144	160	176	192	208	224

Figure 2. Treatment structure employed and field plot plan, Experiment 502, Lahoma, OK.

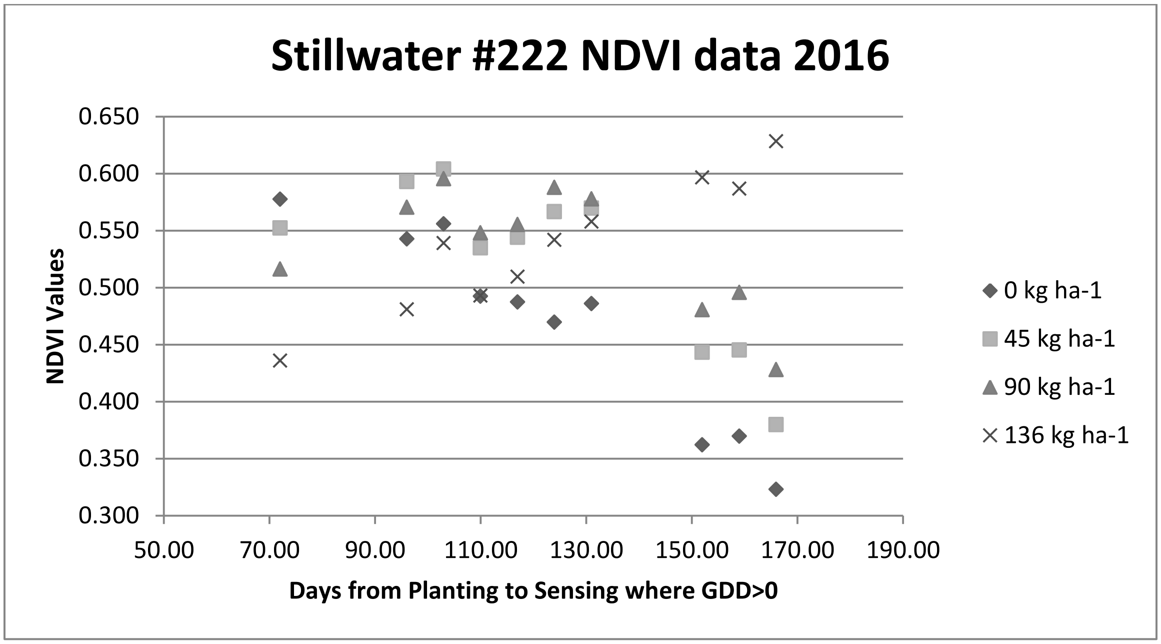

Figure 3. Greenseeker NDVI values plotted over time, Experiment 222, Stillwater, OK 2016 winter wheat.

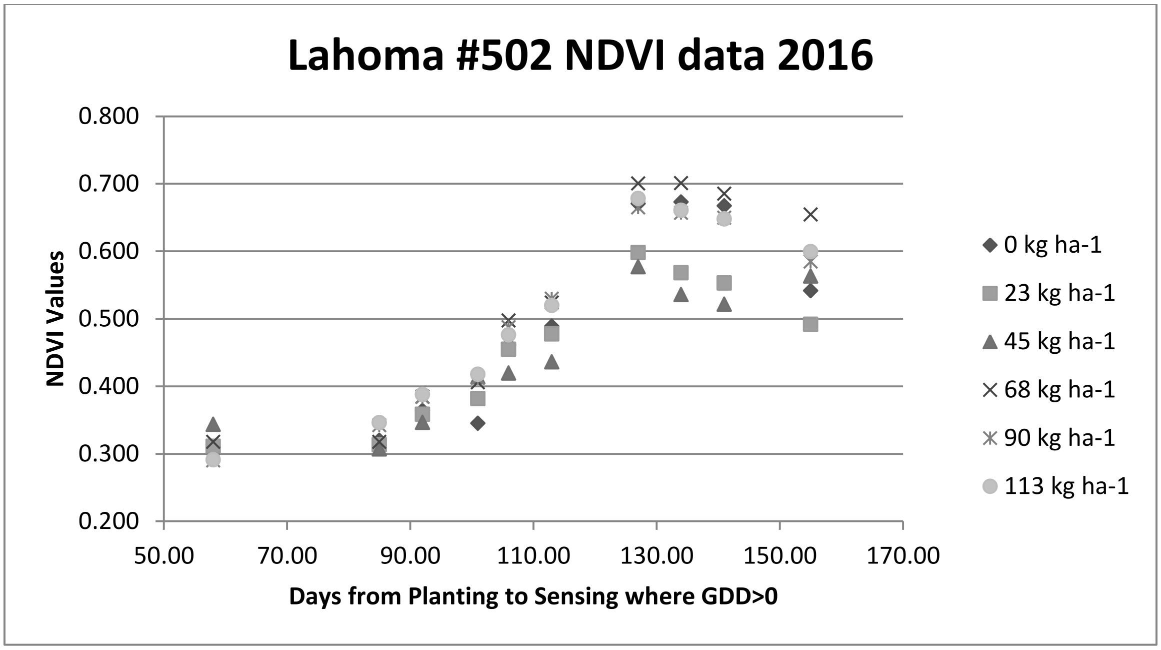

Figure 4. Experiment 502, NDVI data for winter wheat, Lahoma, OK 2016

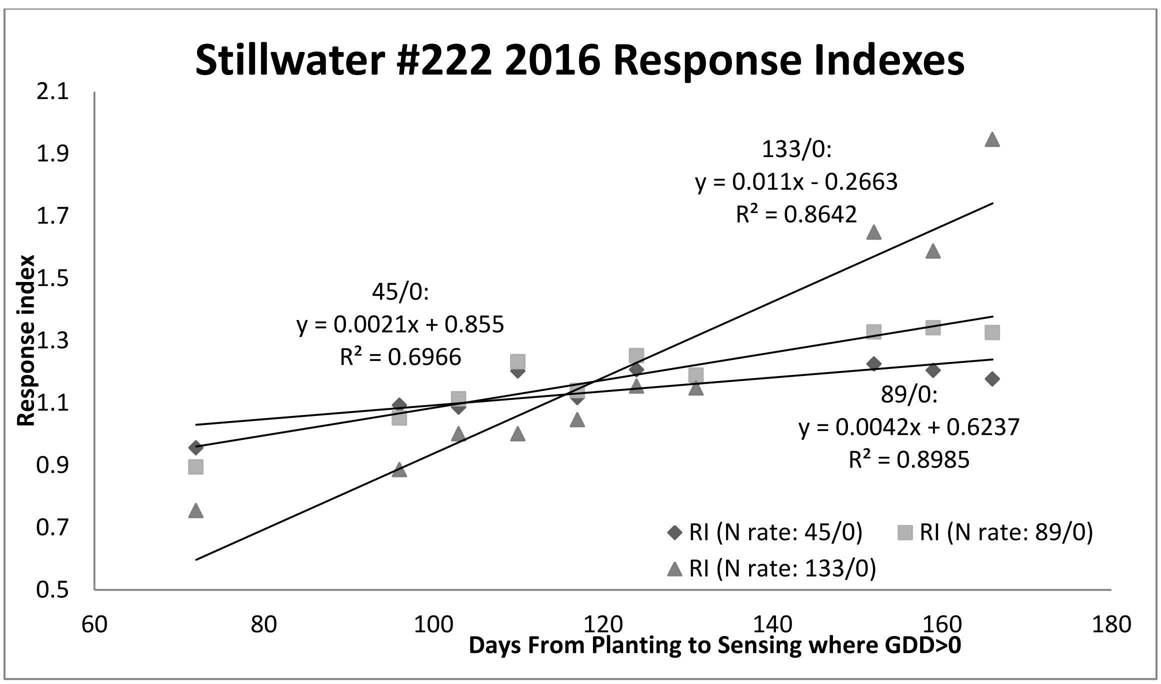

Figure 5. Experiment 222, response indexes for winter wheat, Stillwater, OK, 2016.

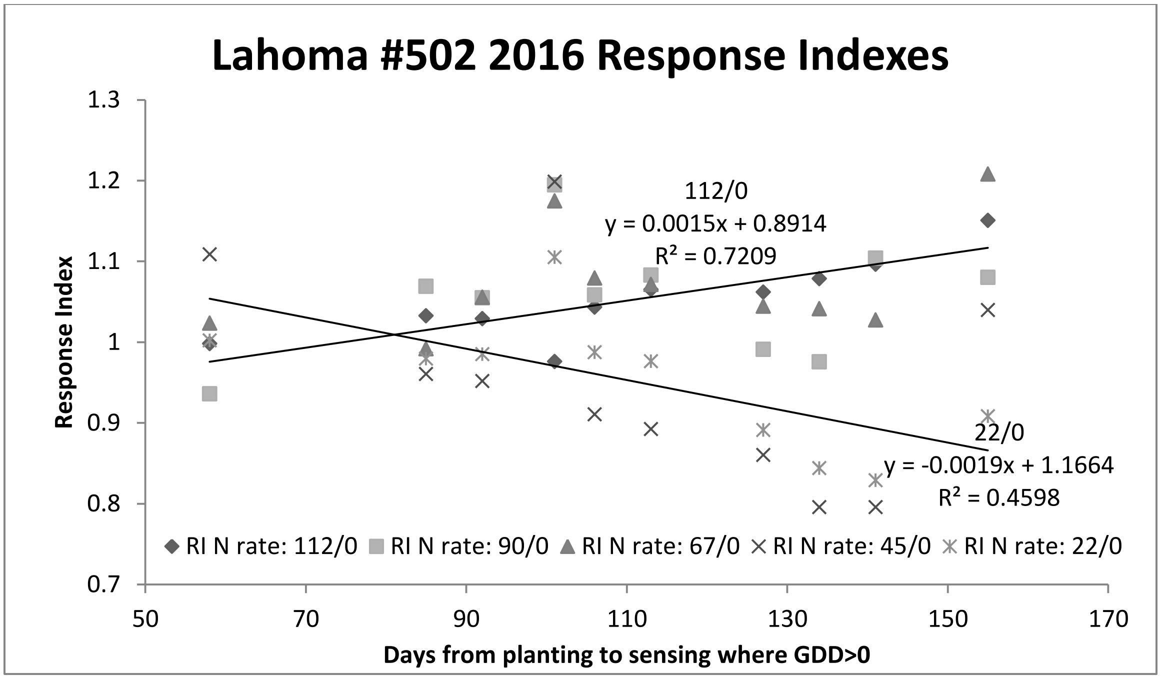

Figure 6. Experiment 502, response indexes for winter wheat, Lahoma, OK, 2016

VITA

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Master of Science

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