ANALYSIS OF THE COEFFICIENT OF VARIATION OF REMOTE SENSOR READINGS IN WINTER WHEAT, AND DEVELOPMENT OF A SENSOR BASED MID-SEASON N RECOMMENDATION FOR COTTON.

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of the
requirements for the
degree of
DOCTOR OF PHILOSOPHY

May, 2008

ANALYSIS OF THE COEFFICIENT OF VARIATION

OF REMOTE SENSOR READINGS IN WINTER

WHEAT, AND DEVELOPMENT OF A Y SENSOR

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COTTON.

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ACKNOWLEDGMENTS

First and foremost, I thank God for giving me the strength and wisdom to complete this degree, without His love and guidance this work would not be possible. I would also like to thank my family for supporting me in my decision to pursue this degree, and always being there for me. I am also very grateful to the Department of Plant and Soil Sciences for the opportunity to work and study at Oklahoma State University. Special thanks to the Soil Fertility Project for their continued support and aid in accomplishing my goals and most of all for their friendship. Specifically, I would like to thank the following graduate and undergraduate members of the Soil Fertility Project: Kyle Freeman, Roger Teal, Kefyalew Desta, Brenda Tubana, Olga Walsh, Clint Mack, Starr Holtz, Kyle Lawles, Kent Martin, Brandon England, Cody Daft, Daniel Edmonds, and Pamela Turner. To my committee members, Dr. Chad Godsey, Dr. Randy Taylor, and Dr. John Solie, I thank you for your encouragement, time, and guidance I received throughout my pursuit of this degree. Finally, heart felt thanks to my major adviser, Dr. Bill Raun, for taking me into the project and allowing me to be a part of something that I feel really makes a difference, and exposing me to the opportunities and responsibilities not only in our country but the developing world.

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ABSTRACT

The GreenSeeker™ hand held sensor is used as a management decision aid in many crops across the world. This sensor measures the normalized difference vegetative index (NDVI) and has been found to be an excellent predictor of plant biomass. In addition, there is a great deal of information that is available and can be utilized from these sensor readings other than just an average value. In an earlier study it was found that the by-plot coefficients of variation (CV) from the GreenSeeker™ sensor NDVI readings had good correlation with winter wheat plant population. From the limited work it was also observed that when RI_{NDVI} (NDVI of fertilized plot / NDVI of check plot) was combined with CV ($RI_{NDVI-CV}$), a better prediction of $RI_{Harvest}$ (yield of fertilized plot / yield of the check plot) was seen than just RI_{NDVI} alone. Because of this a CV adjustment was added to the sensor based mid-season nitrogen (N) rate recommendation in winter wheat. The adjustment was made based on a critical CV value, such that when the measured CV was higher than the critical value, N rates were reduced. When the measured CV was lower than the critical value, N rates were increased. As the CV got closer to zero the N rate increased, up to

the point where theoretical maximum yields could be achieved, and then N rates dropped accordingly. The present study further evaluated the use of CV's determined from NDVI readings collected from both small 1.48m^2 and large 17.0m^2 areas. Trials were established at three locations in the fall of 2005, and were composed of 12 treatments, consisting of 3 seeding rates (45, 90, and 135 kg seed ha^{-1}) by 4 N (0.0, 45, 90, and 135 kg N ha^{-1}) rates organized in a randomized complete block design. In the previous study all treatments were imposed on an already established stand. It was the goal of this study to create variability by adjusting seeding rate. Plots measured 3.05 x 6.1 m, with a sub plot that measured 1.2 x 1.2 m. Plant counts were taken from sub-plots after emergence and sensor readings were collected with a GreenSeeker™ hand held sensor at Feekes growth stages 4, 5, 6, and 7. Grain yield was collected from the center 1 m^2 of the subplot and the center 1.8 m over the length of the plot. Results from this study supported the relationship between CV and plant population and as in the previous work found the critical CV value to be 20. This work did not see an improvement in the prediction of $RI_{Harvest}$ when $RI_{NDVI-CV}$ was used in place of RI_{NDVI}. It was observed that when CV's were less than 5.0 and NDVI values were greater than 0.80 the corresponding $RI_{Harvest}$ was less than 1.2 and often less than 1.0, which suggests that there would be no response to added fertilizer N. This work suggests that current sensor based N rate recommendations that increase N fertilization when the CV drops below 5.0 and the NDVI exceeds 0.80, should result in a reduced N rate. The use of CV values from sensor readings can assist in accounting for stand uniformity, in addition to biomass that is estimated with average NDVI alone.

INTRODUCTION

Plant N losses in winter wheat have accounted for 21% (Harper et al., 1987) to 41% (Daigger et al., 1976) of the unaccounted N using N^{15}. Loss of gaseous N due to denitrification is reported to range from 10% (conventional tillage) to 22% (no-till) in corn (Hilton et al., 1994). In addition, fertilizer N losses in surface runoff range between 1% (Blevins et al., 1996) and 13% (Chichester and Richardson, 1992) of the total N applied; lower levels of losses due to run-off are usually associated with no-till conditions. Another potential pathway for N loss is through leaching of NO^{-}_{3} when fertilizers are applied in excess of crop needs. In cooler, temperate climates, NO^{-}_{3} losses through tile drainage have approached 26 kg N ha^{-1} yr^{-1} under conventional tillage corn when only 115 kg N ha^{-1} was applied (Drury et al., 1996). The benefits would be significant if any one of the pathways could be restricted and loss of N reduced. Johnson and Raun (2003) calculated that a 1% global increase in cereal N use efficiency (NUE) would have a value of $235 million in N fertilizer savings if yields were maintained.

Raun et al. (2002) reported an increase in NUE of >15% when top-dress N fertilization rates were based on optically sensed in-season estimated yield (INSEY). The GreenSeeker™ Hand Held Optical Sensor (NTech Industries, Inc.), developed by Oklahoma State University, senses a 0.6 x 0.01 m area when held approximately 0.6 to 1.0 m from the illuminated surface. The sensed dimensions remain approximately constant over the height range of the sensor. The sensor unit has self-contained illumination in both red (671 ± 10 nm) and NIR (780 ± 10 nm) bands. The device measures the fraction of emitted light in the sensed area that is returned to the sensor (reflectance). The algorithm currently used by N-Tech Industries, "WheatN1.0", includes several distinct components. Raun et al. (2005b) identified these components as : 1) mid-season prediction of grain yield, determined by dividing the normalized difference vegetative index (NDVI), by the number of days from planting to sensing (estimate of biomass produced per day on the specific date when sensor readings are collected); 2) estimating temporally dependent responsiveness to applied N by placing non-N-limiting strips in production fields each year, and comparing the strips to the rest of the farmers field; and 3) determining the spatial variability within each 0.4 m^2 area using the coefficient of variation (CV) from NDVI readings to alter the final N rate.

The yield potential (YP) of many small grain crops, including winter wheat, spring wheat, corn, and rice, has been shown to be predictable mid-season (Lukina et al., 2001; Raun et al., 2001; Raun et al., 2002; Raun et al., 2005b; Teal et al., 2006). Yield potential can be predicted using In Season Estimate of Yield (INSEY), which is calculated by taking NDVI, divided by the number of Growing Degree Days (GDD's) from planting to sensing. This calculation gives a value that is related to biomass produced per day. Correlation between biomass produced per day and final grain yield has been shown to be quite good (Raun et al., 2001). The prediction of potential yield is termed as YP0, when YP0 is multiplied by a response factor the value of YPN, yield potential with added fertilizer N, is created (Hodgen et al., 2005; Mullen et al., 2003; Raun and Johnson, 1999; Raun et al., 2002).

The response index (RI) described by Johnson and Raun (2003), is the response in yield to additional fertilizer nitrogen, calculated by dividing the yield of the high N plot by the yield of the zero N plot. The response index can be determined mid-season (Hodgen et al., 2005; Mullen et al., 2003) and this means that crop response, to additional fertilizer N can be ascertained prior to the time top-dress fertilizer application is made.

Raun et al. (2002) has reported that with the combined use of the RI concept and mid-season prediction of INSEY, an accurate top-dress N rate can be made. This is accomplished by predicting the yield of an area that is not N deficient (N-Rich) and the yield of an area in the field were N status is unknown (farmer practice). Total grain N removed from each area is calculated and the difference between the N-Rich and farmer practice divided by a theoretical efficiency factor is the prescribed top-dress N recommendation. Combined, this set of calculations is termed the nitrogen fertilization optimization algorithm (NFOA) which was outlined by (Lukina et al., 2001).

The coefficient of variation is defined as the standard deviation divided by the mean (Lewis, 1963; Senders, 1958; Steel et al., 1997; Tippett, 1952). Steel et al. (1997) describe the CV as a quantity used by the experimenter in evaluating results from different experiments of the same unit of measure that are possibly conducted by different persons. Little and Hills (1978) suggested that CV can be used to compare experiments involving different units of measurements and/or plot sizes. The CV is a relative measure of variation and varies with every comparison on what is considered large or small, and only experience with similar data can determine its meaning (Steel et al., 1997). Raun et al. (2005a) found that CVs of spectral radiance measurements were useful in detecting the growth stage in corn where within-row-by-plant variability was the greatest.

The results of previous work have shown that both stand density and uniformity affect grain yield. Weisz et al. (2001), reported that as plant stand or tiller density increased, grain yield tended to increase, and the variation within the field decreased. Nielsen (2001) showed that in corn for every 2.56 cm standard deviation of plant-to-plant spacing, there was a decrease in yield of 1567 kg ha^{-1} from the average yield of 9800 kg ha^{-1}. These findings indicate the need to make fertilization recommendations using stand density as a factor. Flowers et al. (2001) validated the use of aerial photography for determining winter wheat tiller density. Using the density estimates, he determined that basing N application on a critical density threshold had an 85.5% success rate. Lukina et al. (2000) observed that as the vegetation coverage increased, the CV of NDVI values decreased. Raun et al. (2001) showed that NDVI values from mid-season sensor readings could be used to predict yield. Thus, combining NDVI and CV independently may result in an improved prediction of yield potential.

In an evaluation of sixty-two wheat field research projects, Taylor et al. (1997) observed that mean yield and CV were negatively correlated. Taylor's work also showed that CVs decreased with corresponding decreases in plot size. Washmon et al. (2002) suggested that if within field CVs could be predicted, the potential response to added nutrients may also be established, and in-season nutrient additions adjusted accordingly. They further stated that the mid-season CV of a field could be equated to the RI, which is currently used by various researchers to determine top-dress fertilizer rates.

Raun et al. (2005b) predicted that when CV was low, a responsive field element should be capable of greater yield than a similarly responsive field element with large CV. In testing this concept, they observed that YPN-CV (predicted yield with added N using INSEY and the CV at the time of sensing) values more closely followed observed yield than did YPN (predicted yield using the INSEY equation) values. Morris et al., (2006) noted that when plot CVs of NDVI readings were >18, maximum yields could not be achieved when N fertilizer was delayed until mid-season. When plot CVs were < 18, delaying all N fertilization until mid-season resulted in maximum yields and increased NUE.

The current GreenSeeker™ sensor collects more than 10 readings within each 0.4 m^2 traveling at 10 mph (Raun et al., 2005c). Raun et al. (2005b) further stated that the 10 readings collected from each 0.4 m^2 are considered to be sufficient to obtain a composite sample to reliably estimate the average, understanding that the 10 sensor readings were representative of the variability from the same 0.4 m^2 surface area.

The variable rate method is a vast improvement on the use of 15 soil samples to represent a unit area that could range from a few acres to several hundred acres (Johnson et al., 2000). If the goal is to maximize crop NUE, the use of average NDVI's presents a problem. Without the addition of a CV adjustment, two 0.4 m^2 areas with similar NDVI's would receive the same treatment, but could need two different rates. A good stand of nutrient deficient wheat may have the same average NDVI as a poor stand of nutrient enriched wheat. The ability to index plant stand density on-the-go may provide the needed solution. The effect of plant population and tiller density on the GreenSeeker™ sensor's ability to correctly determine yield potential has not yet been assessed.

When first investigated, the application of using CV's from sensor NDVI readings. In their study a relationship between CV and plant population was found to exist with a critical CV range of 17 – 20, which was determined using the Cate-Nelson model. Using a CV derivation of RI_{NDVI}, the prediction of $RI_{Harvest}$ was improved when compared to the original RI_{NDVI} calculation (Arnall et al., 2006).

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HYPOTHESES AND OBJECTIVES

The hypotheses for this study were: (1) the use of CV's of sensor readings will better predict $RI_{Harvest}$; and (2) RI_{NDVI} collected from the sub-plots will predict $RI_{Harvest}$ as well as the RI_{NDVI} collected from the main plots. The objectives of this work are to utilize the coefficient of variation measured using spectral radiance measurements and plant population at early growth stages; and to evaluate RI_{NDVI} as a mid-season predictor of $RI_{HARVEST.}$ In addition, the RI_{NDVI} collected from the sub-plots will be compared to the RI_{NDVI} collected from the corresponding plot. This will be done to compare the small plot research to the larger scale work.

MATERIALS AND METHODS

This trial was established at three locations: Lake Carl Blackwell, Perkins Research Station, and Hennessey. Soil classification and characteristics at each site are described in Table 1. Prior to the initiation of the field trials, a series of soil samples were taken at each location and the initial soil test results are reported in Table 2.

Each trial evaluated three seeding rates (45, 90 and, 135 kg ha^{-1}), and four pre-plant N rates (0, 45, 90 and, 135 kg ha^{-1}), for a total of twelve treatments (Table 3). Treatments were arranged in a randomized complete block design with 3 replications. Plot size was 3.0 m by 6.0 m with a 6.0 m alley between replications. Preplant N was applied using urea (46-0-0) and incorporated into the soil using conventional tillage practices. Addition of other nutrients was on an as needed basis.

In the 2006-2007 crop year, the Perkins site was converted into a no-till production system. Due to this change in cultural practice, preplant fertilizer was applied using UAN (28-0-0) liquid fertilizer as the N source.

Sub-plots were established within each plot soon after germination at growth stage Feekes 1(emergence) so that the plots could be oriented with the seed rows. Sub-plot size measured 1.48 m^2, with each plot containing eight rows spaced 15 cm apart. Plant stand density was estimated for each plot at Feekes

1 (Large, 1954) by counting all plants within four rows randomly selected in each sub-plot. Spectral radiance measurements were taken using the GreenSeeker™ Hand Held Optical Sensor Unit. As described by Raun et al. (2001), the device uses a patented technique to measure crop reflectance and to calculate NDVI. The equation for this calculation is shown below.

$$NDVI = \frac{\rho_{NIR} - \rho_{\text{Red}}}{\rho_{NIR} + \rho_{\text{Red}}}$$

Where ρ_{NIR} - Fraction of emitted NIR radiation returned from the sensed area (reflectance)
ρ_{Red} - Fraction of emitted Red radiation returned from the sensed area (reflectance)

Sensor readings were collected from the main plots and sub-plots separately, at five growth stages: Feekes 3, 4, 5, 6 and 7.

For this study, CV's of sensor readings were calculated by computing the standard deviation and average of each plot and sub-plot from the raw data collected by the sensor.

The center 1 m^2 of each subplot area was harvested at maturity using a hand sickle and cutting slightly above the crown, collecting all surface biomass. Harvested samples were weighed, oven-dried at 70°C for 72 hours and reweighed to determine percent moisture. Samples were threshed using a mechanized thresher and grain collected. Grain weights were rerecorded and straw and grain yields determined accordingly. The center 2 m of the remaining 15m of the plots was harvested with a Massey Ferguson 8XP experimental combine in late May or early June at all experimental sites. Data for grain yield and percent moisture content was collected using the Harvest Master yield monitoring computer. Grain sub-samples were collected, oven-dried at 70°C for 72 hours and processed to pass a 106 um (140 mesh screen) for total N analysis using a Carlo Erba NA 1500 dry combustion analyzer (Schepers et al., 1989). Total N uptake was determined by multiplying percent grain N with grain yield. Nitrogen use efficiency was calculated by subtracting N uptake in the 0-N treatment from N uptake in the fertilized plot and divided by the rate of N applied. Statistical analysis was performed using SAS for Windows (SAS, 2002). Analysis of variance on rep-trt models, linear regression, and multiple range mean separation procedures were used.

RESULTS AND DISCUSSION

Work by Arnall et al., (2006) first evaluated the CV of sensor readings and how they were related with plant population of winter wheat. In this paper a critical CV range of 17 to 20 was observed. The present study uses combined data from Arnall et al. (2006). The relationship between CV from sensor readings collected between Feekes growth stages 4 and 6, and population is reported in Figure 1. The critical CV was determined using a linear-linear model from the NLIN procedure in SAS and was calculated at 19.97 and a plant population of 76.54 plants m^2. This fits within the range found in a previous study and with the critical CV level that Morris et al. (2006) observed where the winter wheat crop no longer responded to added fertilizer N.

As the CV increased from sensor readings, grain yield decreased (Figure 2). The slope was significantly different from zero, and the overall trend evident from the combined data set. When the data from only the 1.48 m^2 plots was plotted the relationship improved, with an r^2 of 0.14 (Figure 3). Using only the data from the larger plots, the linear relationship between CV and grain yield resulted in an r^2 of 0.27 (Figure 4). While not conclusive, this suggests that CV data could be more useful when collected on a coarser scale. As has been shown in several publications (Arnall et al., 2006; Mullen et al., 2003; Raun et al., 2001; Teal et al., 2006) the relationship between $RI_{Harvest}$ and RI_{NDVI} is not 1 to 1, Figure 5. When the relationship between $RI_{Harvest}$ and RI_{NDVI} was evaluated from both 1.48 m^2 and 17.09 m^2 plots, an r^2 of 0.16 was found. Similarly, correlation was poor when only data for the 1.48 m^2 plots was included (Figure 6). However, when the data was limited to only those points from the large plots (Figure 7) the relationship was slightly improved with an r^2 of 0.26.

Work by Arnall et al. (2006), showed that the predictive nature of RI_{NDVI} was improved when it was multiplied by a CV factor. When the same derivation was followed with the data from this experiment the new $RI_{CV-NDVI}$ value had a very poor relationship with $RI_{Harvest}$ (Figure 8.). Figures 9 and 10 show the relationship of $RI_{Harvest}$ to $RI_{CV-NDVI}$ from the sub plots and large plots respectively. The r^2 of the relationship for large plots was somewhat better with an r^2 of 0.18.

Further evaluation prompted looking at $RI_{Harvest}$ and RI_{NDVI} based on subsets of CV values. Figures 11 through 15 show the relationship when CV ranged from 0 - 5, 5 - 10, 10 - 15, 15 – 20, and 20+, respectively. Similar to that observed by Arnall et al. (2006), as the CV increased the ability to correctly predict $RI_{Harvest}$, with RI_{NDVI}, also increased. For the CV ranges of 5-10, 10-15, and 15-20 (Figures 12, 13, and 14) the slope and intercept components from these linear equations were quite similar (0.4475x + 0.7236, 0.4294x + 0.7343, and 0.4034x + .7068, respectively).

When CV and NDVI from all sub plot and large plots were graphed, a negative relationship was observed (Figure 16.) This was expected since it requires a very good stand of winter wheat to have low CV's, and because whenever soil is present in the field of view, CV will be increased. Figures 17 and 18 illustrate the relationship between CV and NDVI when only the sub plot and large plot data were included. There was no discernable difference in the relationship when sample area was considered. As CV's approached 5 or less, NDVI's seldom were below 0.60. This was also observed in Table 5 where average, minimum, and maximum NDVI values for the range in CV's were reported.

The relationship between $RI_{Harvest}$ and NDVI when data was restricted to CV's less than 10 is illustrated in Figure 19. The importance of this graph is that it shows that in only one instance, $RI_{Harvest}$ was greater than 1.2 when NDVI was above 0.80.

Figure 20, illustrates the frequency of occurrence of CV's measured from plots used to analyze RI. Twenty eight percent of the data had a CV that fell within the CV range of 0-5, while forty two percent fell within the 5-10 CV range. Thus, seventy percent of the plots had CV's within the range where RI_{NDVI} was poorly correlated with $RI_{Harvest}$. Figure 21, exhibits the distribution of the NDVI readings recorded from all plots. All ranges of NDVI values contained 13 to 19% of the samples for both sub plot and large plot measurements with the exception of the 0.2 to 0.3 and the 0.7 to 0.8 NDVI ranges. For both plot sizes 25% of the samples fell within the 0.7 to 0.8 NDVI range, only 4% and 3% of the samples fell within the 0.2 to 0.3 range for the 1.48 m^2 and 17.09 m^2 plots, respectively.

The current method used to adjust N rates for 1m^2 micro plots in OSU field trials, utilizes a CV adjustment of percent change in yield where predicted yield after fertilization (YPN_{CV}) is equal to YPN - (YPN * 0.017 * CV -.177). This equation was generated from the relationship between CV and final grain yield, where grain yield in Mg ha^{-1} = -0.400 * CV + 2.656. Using this approach the critical CV value was set at 10. At a CV of 5 the predicted yield was increased by 9.2%, 12.6% at CV of 3, and 16% increase when the measured CV was 1.

For a crop of winter wheat to have a CV < 5.0 and NDVI > 0.80 there must be nearly 100% canopy cover with no soil or residue in the sensors field of view and the crop must be a very dark green. When this is the case it is very unlikely that there are any major nutrient deficiencies, and additional N applications should be avoided. Recognizing the need for applying additional N when CV's are low (same average NDVI values) is a concept that merits further attention. However, this approach should apply obvious restrictions when NDVI values are high. From the results of this paper an if-then statement that follows should be included in the algorithm,

IF [logical statement (NDVI ≥ 0.80 & CV ≤ 8)] , [value if true (YPN)] , [value if false (YPN_{CV})]])

CONCLUSIONS

There is a great deal of information when collecting sensor readings using the GreenSeeker™ in addition to the obvious average NDVI values. This study shows that the CV of sensor readings can help to better understand how the crop will respond to fertilizer N. But this study showed that the original $RI_{NDVI-CV}$ equation that was proposed in the Arnall et al. (2006) paper does not improve prediction of $RI_{Harvest}$. So whether the implementation of this knowledge is through if-then statements in the NFOA or through CV adjustments of RI_{NDVI}, the application of top-dress N in wheat should be improved. The combination of the two would likely be the most effective approach. Much more data is needed to better understand all of the relationships between CV and $RI_{Harvest}$ and CV and yield. Only through applied field trial implementation we will gain a better understanding of the importance of CV's on sensor based N rate recommendations. This study also observed that there could be situations where the use of CV adjustments produces higher than needed N rate recommendations. However, it must be understood that the occurrence of environments where NDVI's are greater than 0.8 and CV's less than 8.0 are quite uncommon at the time when winter wheat is typically top-dressed. These circumstances require optimum growth during the entire season, in addition when these situations are seen it is usually much later in the cropping season.

This study showed that modifications are needed for the computation of $RI_{NDVI-CV.}$ The decision to utilize a CV adjusted YP, YPN_{CV}, was supported by this work, with the understanding that when the extreme upper limit of NDVI and lower limit of CV was present, YPN should be used. This study also indicates the need to improve the prediction of $RI_{Harvest}$ when CV is below 5 as this was a point where RI_{NDVI} had the poorest correlation with $RI_{Harvest}$.

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Table 1. Soil series classification and description, for the three sites evaluated.

Location	Soil Description	
Lake Carl Blackwell	Port silt loam	fine-silty, mixed, superactive, thermic Cumulic Haplustoll
Perkins Station	Konawa fine sandy loam	fine-loamy, mixed, active, thermic Ultic Haplustalf
	Teller sandy loam	fine-loamy, mixed, active, thermic Udic Argiustoll
Hennessey	Bethany silt loam	fine, mixed, superactive, thermic Pachic Paleustoll

Table 2. Initial soil test results (0-15cm) from composite samples collected before each trial was initiated, reported in (kg ha^{-1})

Location	NO_3	NH_4	P	K	pH
	----		mg kg^{-1}	----	
Lake Carl Blackwell	12.9	9.6	15.0	150	6.4
Perkins Station	9.5	8.2	21.0	262	5.4
Hennessey	30.0	8.6			6.4

Table 3. Treatment structure implemented at all three sites, with associated seeding and N rate in a full factorial arrangement of treatments.

Treatment	Seeding Rate (kg ha^{-1})	N-Rate (kg ha^{-1})
1	45	0
2	45	45
3	45	90
4	45	135
5	90	0
6	90	45
7	90	90
8	90	135
9	135	0
10	135	45
11	135	90
12	135	135

Table 4. Planting date, variety, Feekes 6 date, Feekes 6 GDD>0, and harvest date for all experimental sites (Lake Carl Blackwell, Perkins Station, and Hennessey) in 2005-2007.

Location	**Crop Year**	**Planting Date**	**Variety**	**Feekes 6 Sensing**	**GDD > 0**	**Harvest date**
Lake Carl Blackwell	2005	10/20/2004	2174	3/25/2005	109	6/23/2005
	2006	10/12/2005	Fanin	3/27/2006	115	6/16/2006
Perkins Station	2005	10/18/2004	Jagger	3/25/2005	102	6/07/2005
	2006	10/10/2005	Jagger	3/27/2006	117	5/30/2006
Hennessey	2005	10/24/2004	Overley	3/28/2005	96	6/06/2005
	2006	10/17/2005	Overley	3/15/2006	102	6/06/2006
	2007	10/12/2006	Overley	3/21/2007	102	7/21/2007

Table 5. Average, minimum, and maximum NDVI values for ranges of CV collected from 1.48m^2 sub-plots and 17.09 m^2 plots.

CV	1.48 m^2 sub-plot			17.09 m^2 sub-plot		
Range	Average	Minimum	Maximum	Average	Minimum	Maximum
0 -5	0.764	0.359	0.892	0.801	0.682	0.896
5 – 8	0.610	0.232	0.840	0.673	0.385	0.872
8 – 10	0.511	0.218	0.731	0.559	0.226	0.740
10 – 15	0.484	0.235	0.746	0.478	0.238	0.693
15 - 20	0.429	0.279	0.673	0.397	0.244	0.628
20 +	0.325	0.235	0.484	0.391	0.291	0.532

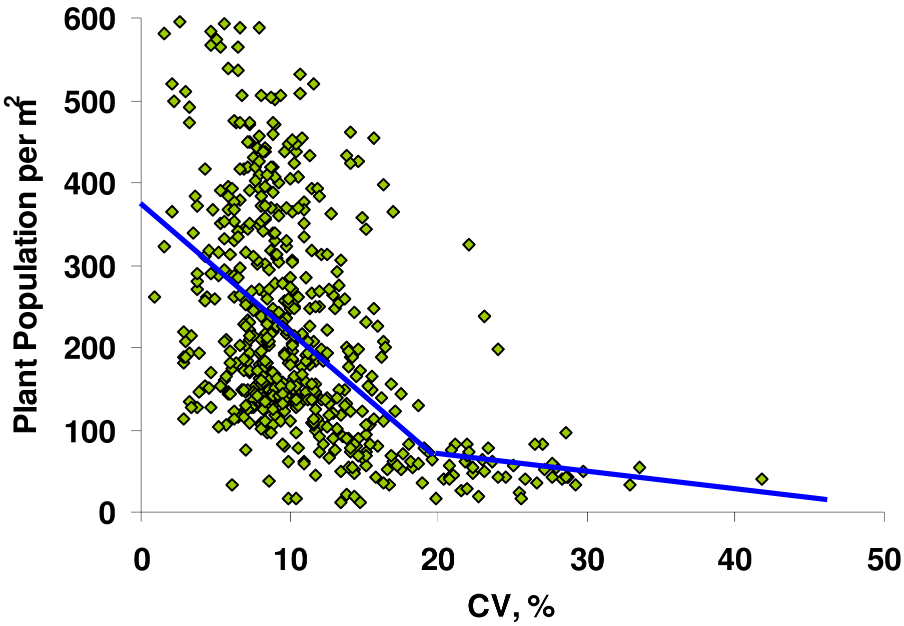

Figure 1. Relationship between the CV from NDVI sensor readings collected between Feekes growth stages 4 and 6, and plant population of winter wheat within 1.48 m^2 areas (fourteen site-years, 2003-2007, and ten varieties). The critical CV of 19.97 was determined using a linear-linear model, Joint level = 76.54, intercept = 373.78, and r^2 = 0.24.

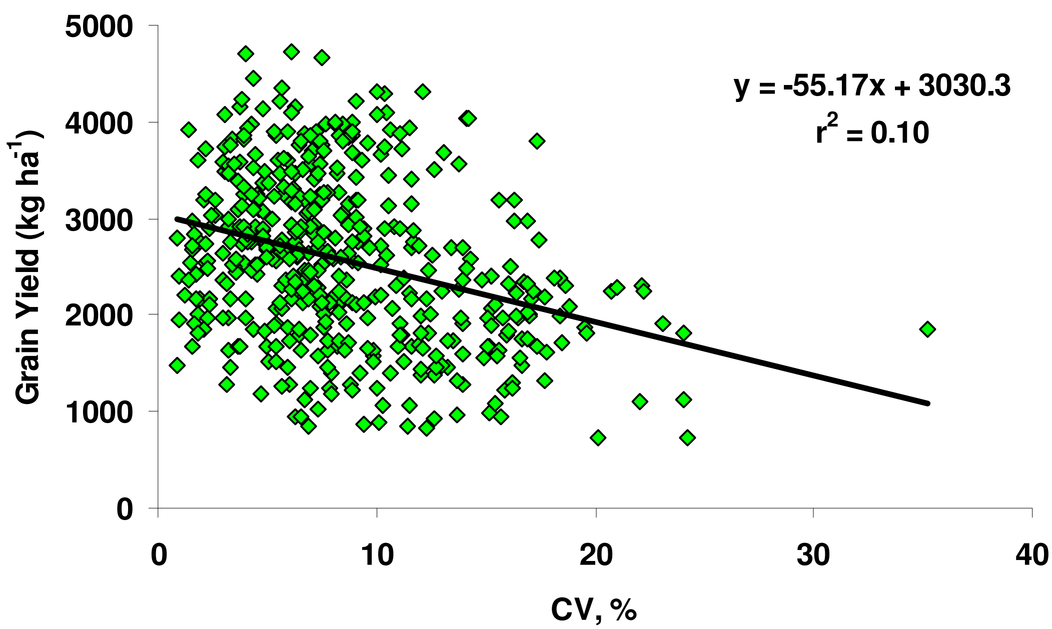

Figure 2. Relationship between CV from NDVI sensor readings collected between Feekes growth stages 4 and 6, and winter wheat grain yield kg ha^{-1} (three locations, 2005-2007, and three varieties) taken from all sub (1.48 m^2) plots and large (17.09 m^2) plots.

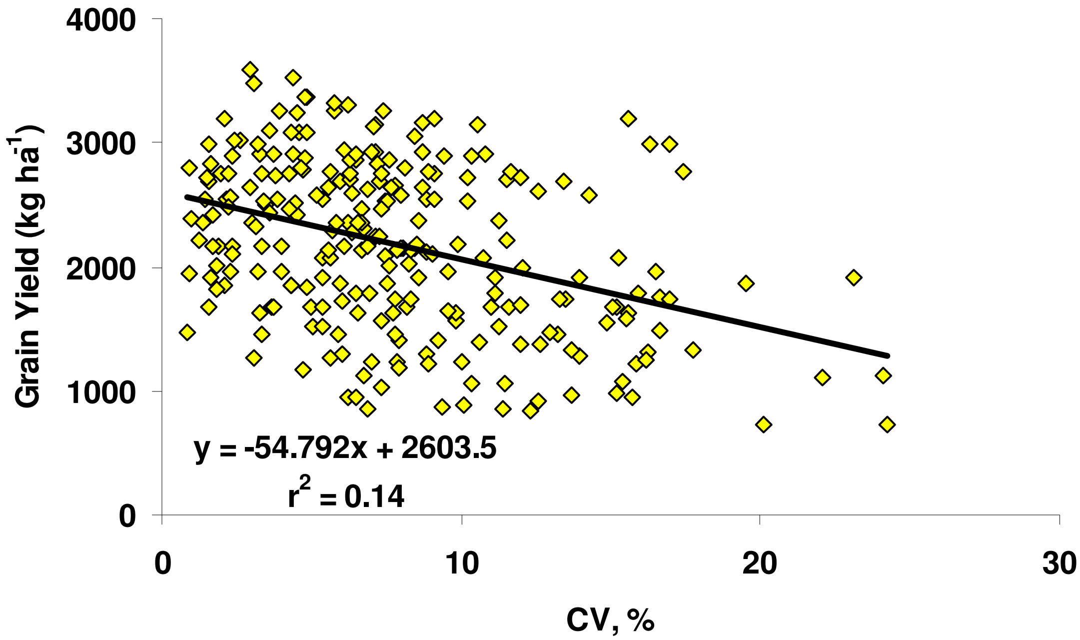

Figure 3. Relationship between the CV from NDVI sensor readings collected between Feekes growth stage 6, and winter wheat grain yield kg ha^{-1} (three locations, 2005-2007, and three varieties) taken from all sub (1.48 m^2) plots.

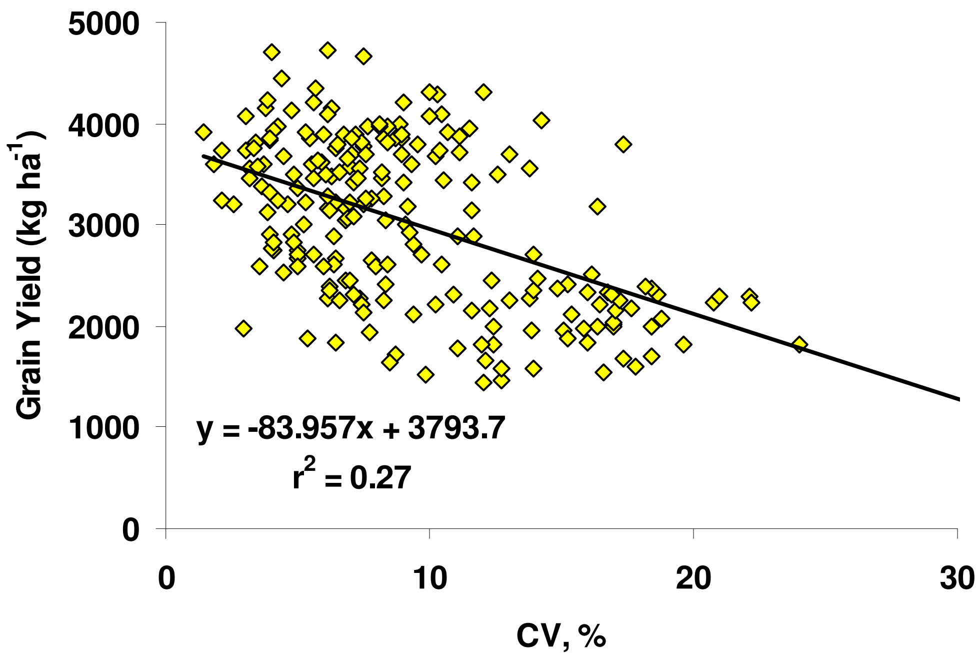

Figure 4. Relationship between the CV of NDVI readings collected at Feekes growth stage 6, and winter wheat grain yield kg ha^{-1} (three locations, 2005-2007, and three varieties) taken from all large (17.09 m^2) plots.

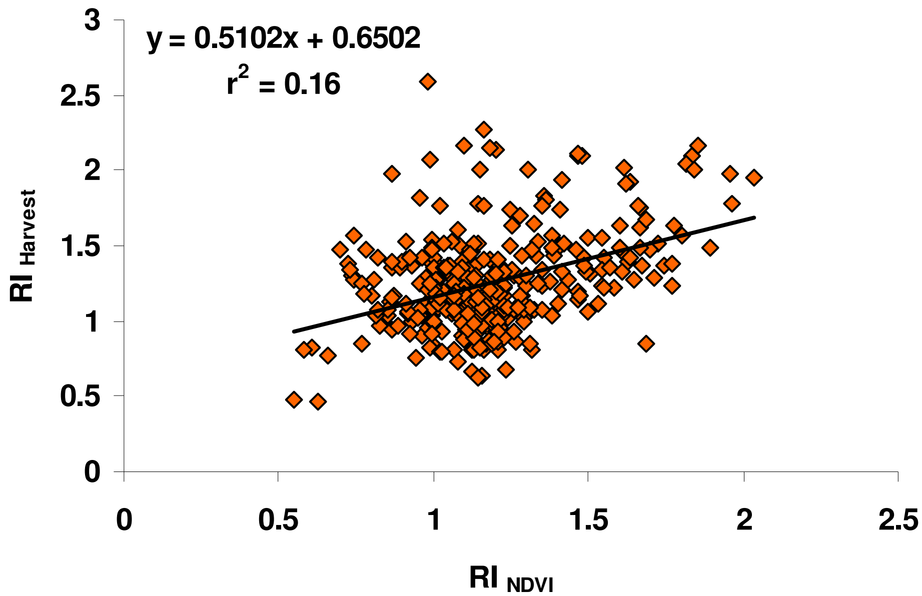

Figure 5. Relationaship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) collected at Feekes growth stage 6 from all sub (1.48 m^2) plots and large (17.09 m^2) plots.

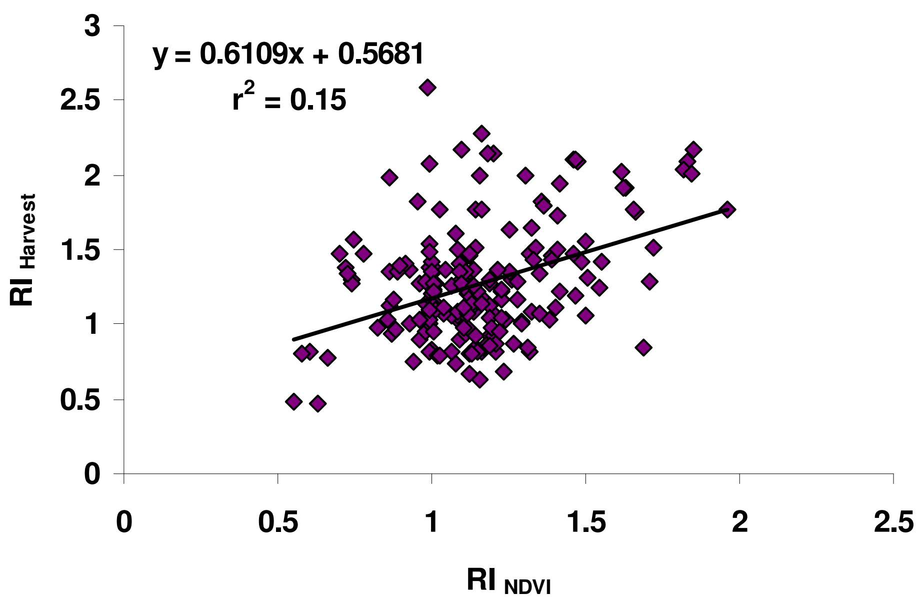

Figure 6. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from all sub (1.48 m^2) plots collected at Feekes growth stage 6.

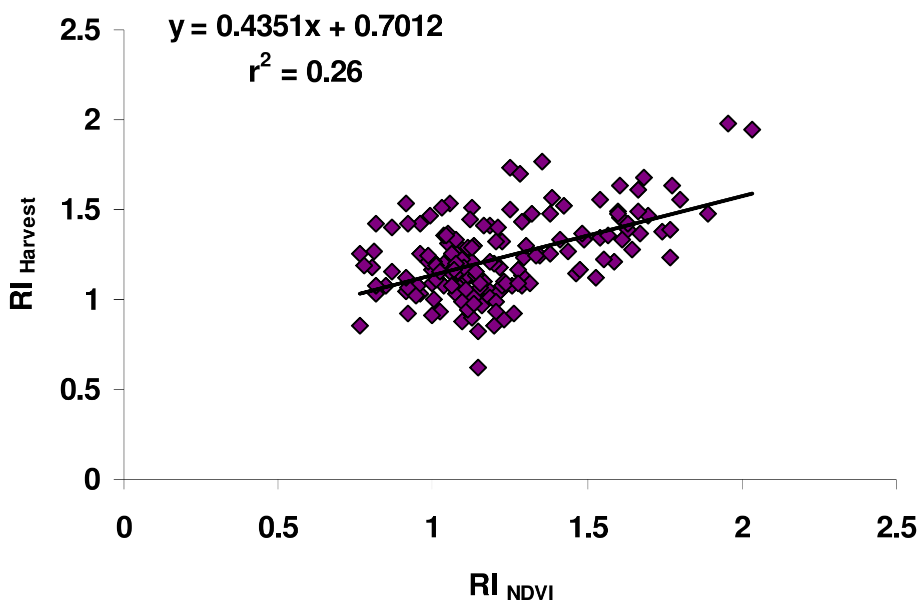

Figure 7. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from all large (17.09 m^2) plots collected at Feekes growth stage 6.

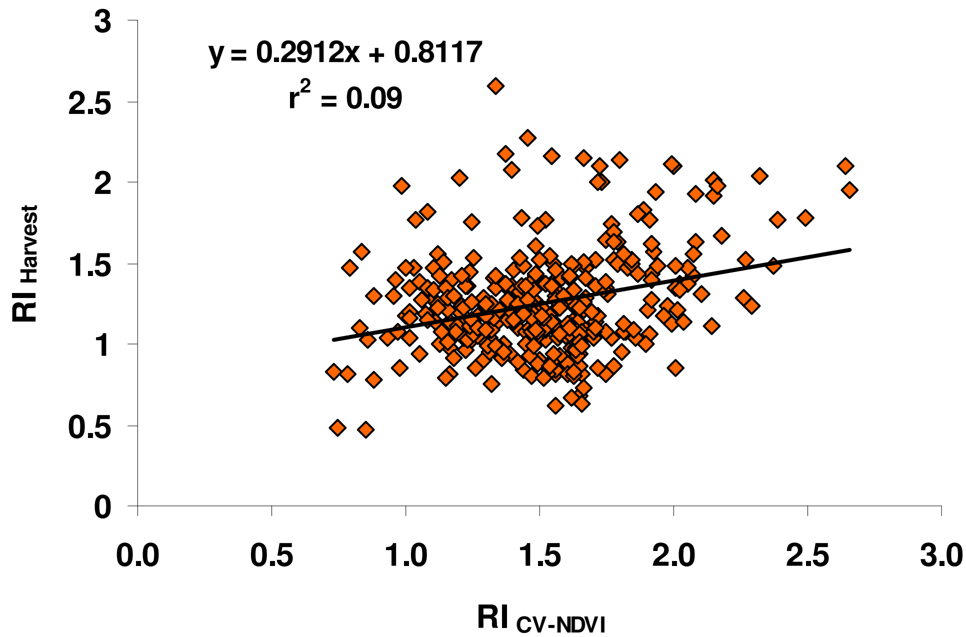

Figure 8. Relationship of $RI_{Harvest}$ (yield of fertilized plot / yield of control) and $RI_{CV\text{-}NDVI}$ {(NDVI of the fertilized plot / NDVI of the control) x ((max CV – control CV) / (max CV – critical CV))}from all sub (1.48 m^2) plots and large (17.09 m^2) plots collected at Feekes growth stage 6.

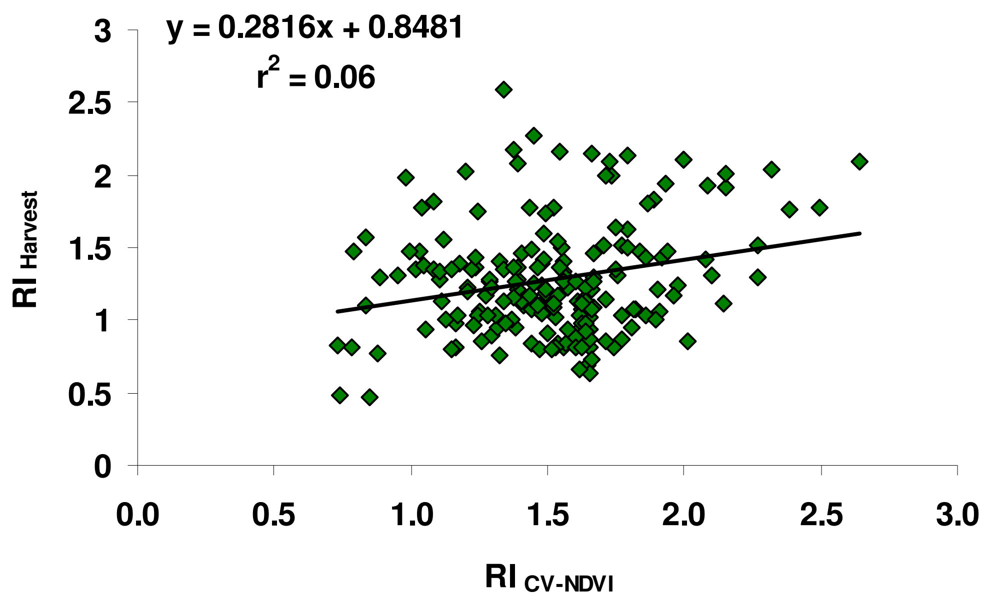

Figure 9. Relationship Comparison of $RI_{Harvest}$ (yield of fertilized plot / yield of control) versus $RI_{CV\text{-}NDVI}$ {(NDVI of the fertilized plot / NDVI of the control) x ((max CV – control CV) / (max CV – critical CV))}from all sub (1.48 m^2) plots collected at Feekes growth stage 6.

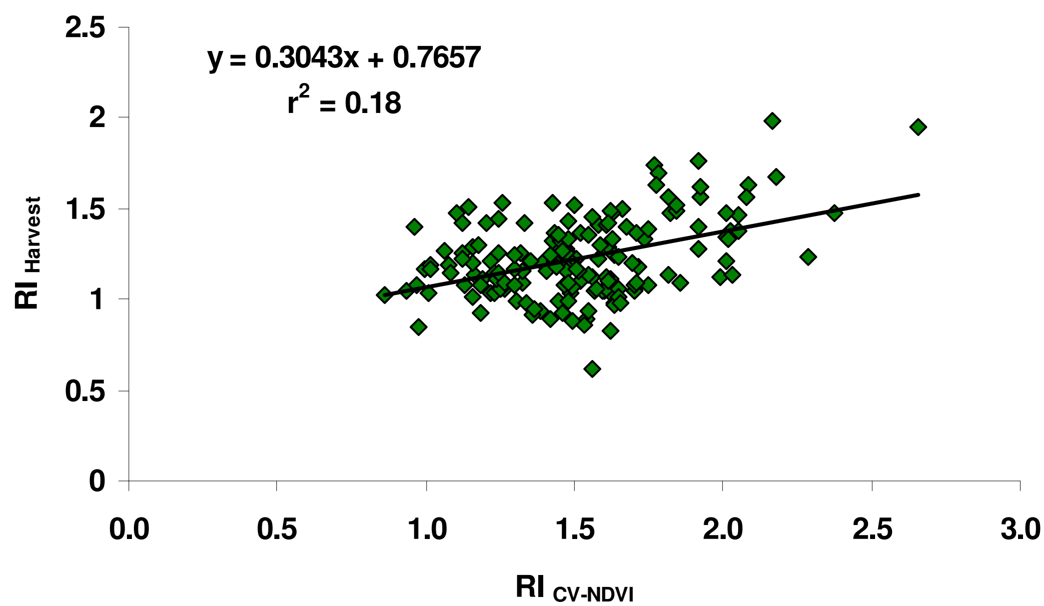

Figure 10. Relationship between of $RI_{Harvest}$ (yield of fertilized plot / yield of control) and $RI_{CV\text{-}NDVI}$ {(NDVI of the fertilized plot / NDVI of the control) x ((max CV – control CV) / (max CV – critical CV))}from all large (17.09 m^2) plots collected at Feekes growth stage 6.

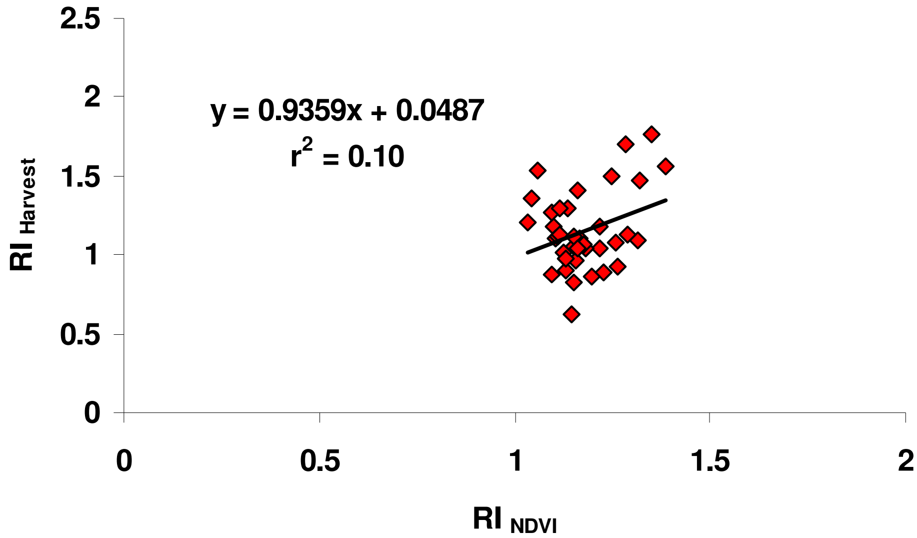

Figure 11. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from all large (17.09 m^2) plots where measured CV ranged from 0.0 to 5.0, collected at Feekes growth stage 6.

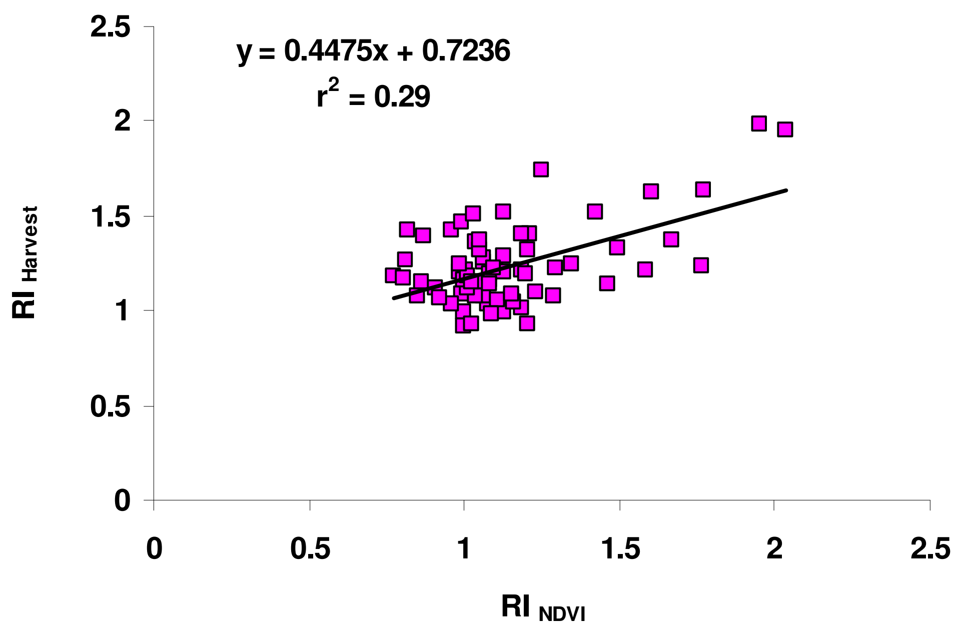

Figure 12. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from all large (17.09 m^2) plots where measured CV ranged from 5.0 to 10.0, collected at Feekes growth stage 6.

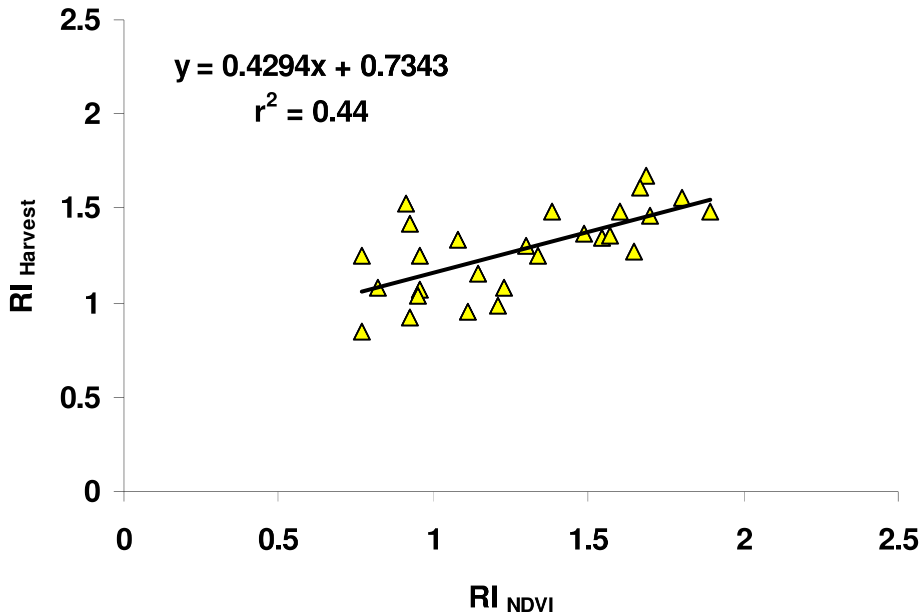

Figure 13. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from all large (17.09 m^2) plots where measured CV ranged from 10.0 to 15.0, collected at Feekes growth stage 6.

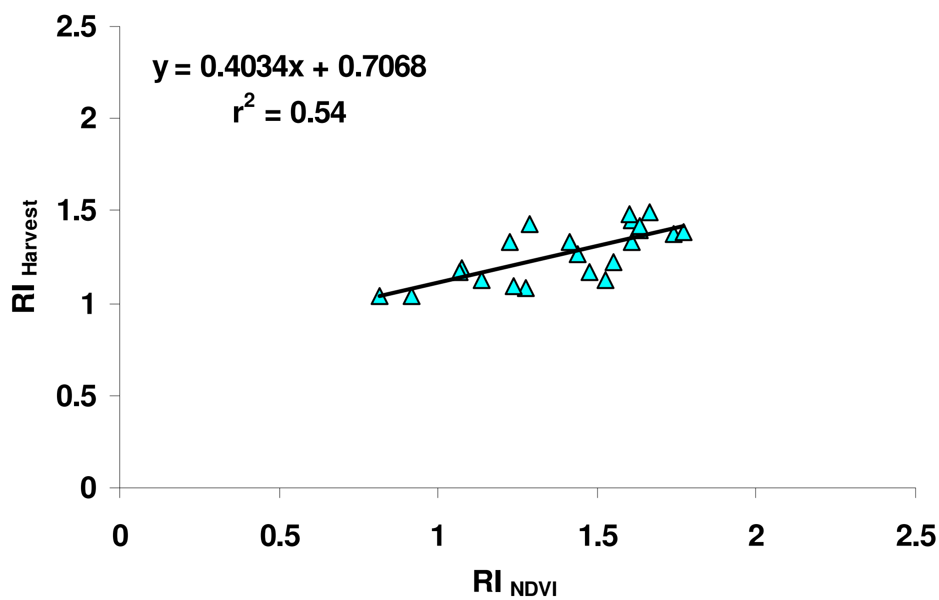

Figure 14. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from all large (17.09 m^2) plots where measured CV ranged from 15.0 to 20.0, collected at Feekes growth stage 6.

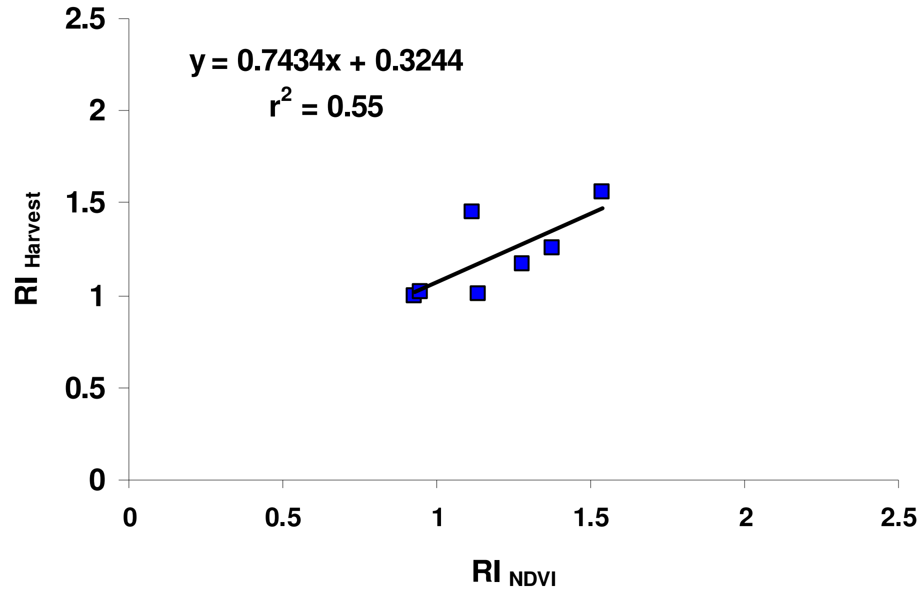

Figure 15. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) andRI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from all large (17.09 m^2) plots where measured CV ranged from 20.0 or greater, collected at Feekes growth stage 6.

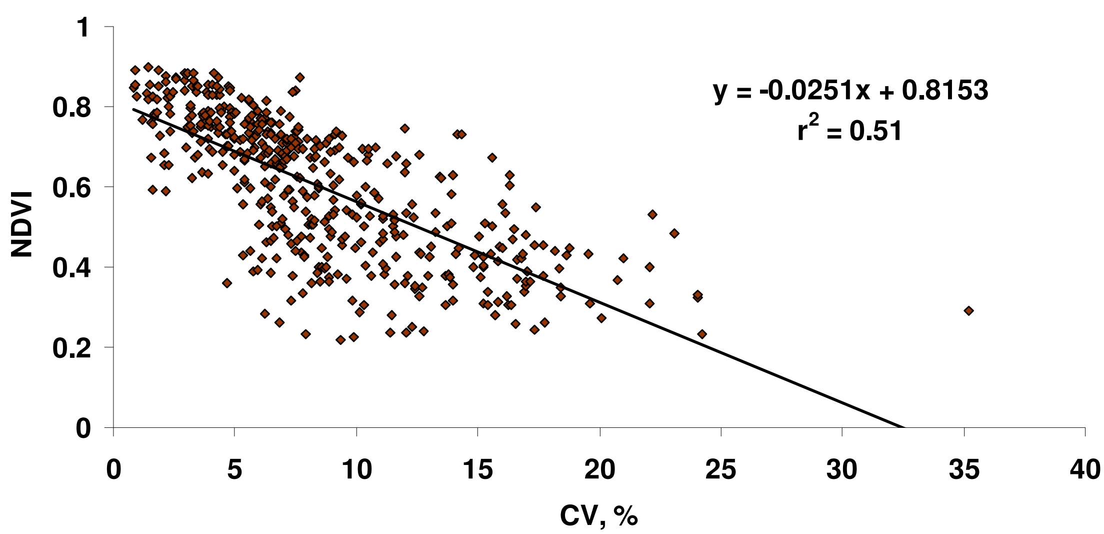

Figure 16. Relationship between the CV of NDVI readings and NDVI readings (three locations, 2005-2007, and three varieties) taken from all sub (1.48 m^2) plots and large (17.09 m^2) plots, collected at Feekes growth stage 6.

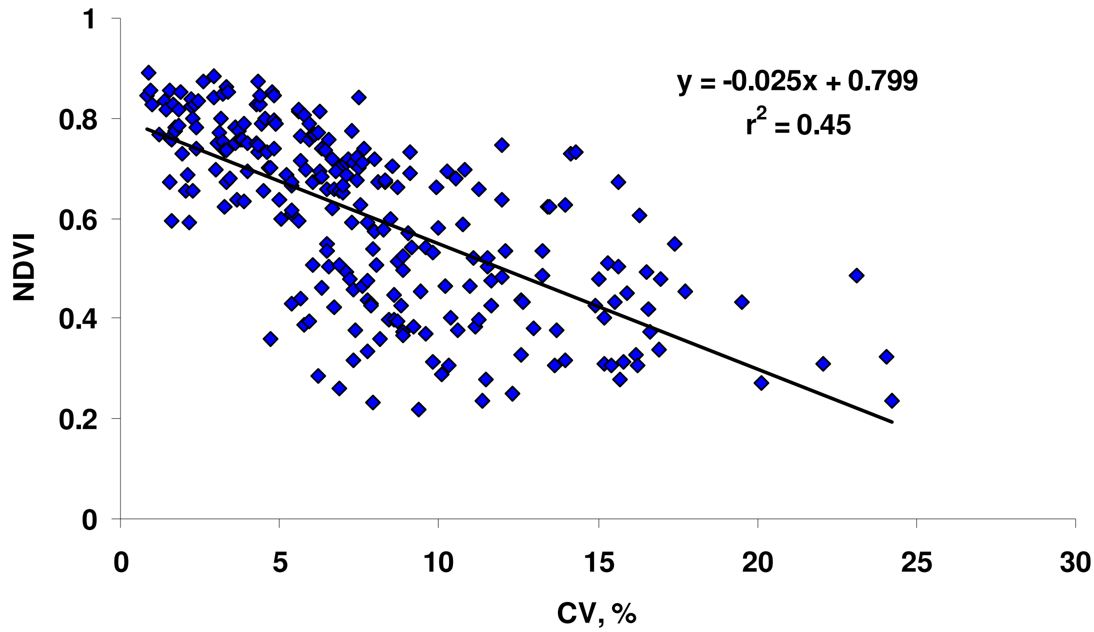

Figure 17. Relationship between the CV of NDVI readings and NDVI readings (three locations, 2005-2007, and three varieties) taken from all sub (1.48 m^2) plots, collected at Feekes growth stage 6.

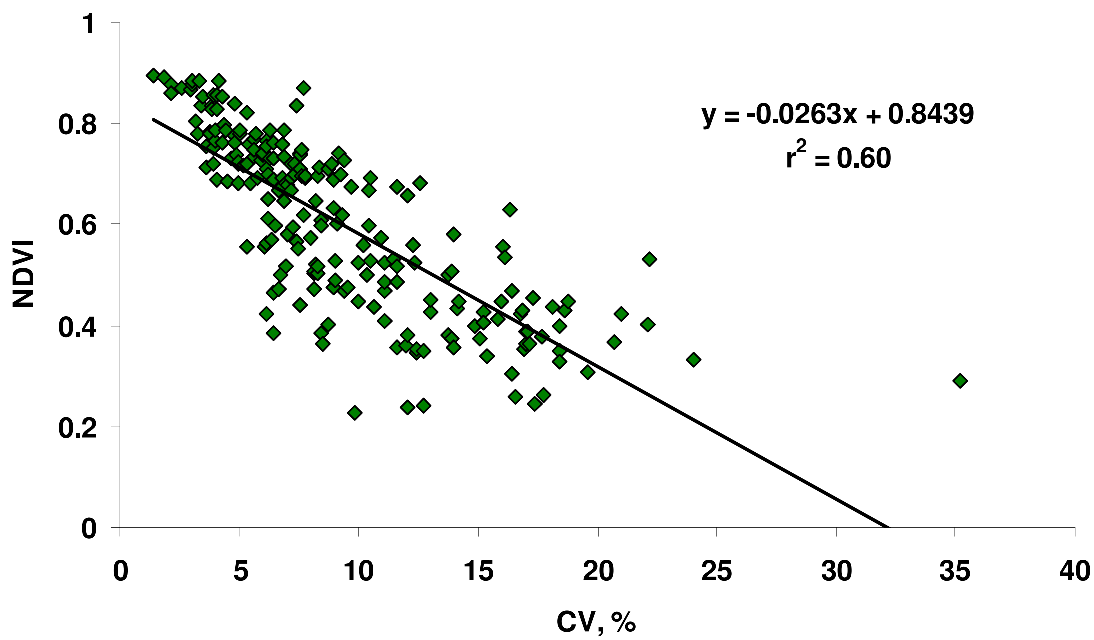

Figure 18. Relationship between the CV of NDVI readings and NDVI readings (three locations, 2005-2007, and three varieties) taken from all large (17.09 m^2) plots, collected at Feekes growth stage 6.

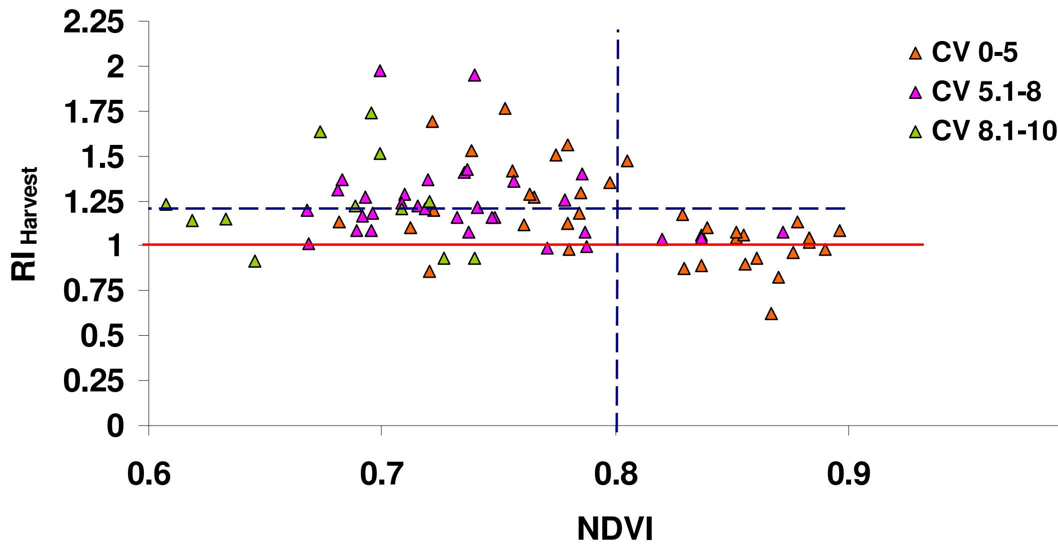

Figure 19. Comparison of $RI_{Harvest}$ (yield of fertilized plot / yield of control) versus NDVI from all large (17.09 m^2) plots where measured CV ranged from 0.0 to 5.0, collected at Feekes growth stage 6. The red line indicates a $RI_{Harvest}$ = 1.0, where <1.0 signifies no response in yield to fertilizer nitrogen. The blue dashed line shows that at a NDVI of ≥ 0.80 $RI_{Harvest}$ does not exceed 1.25.

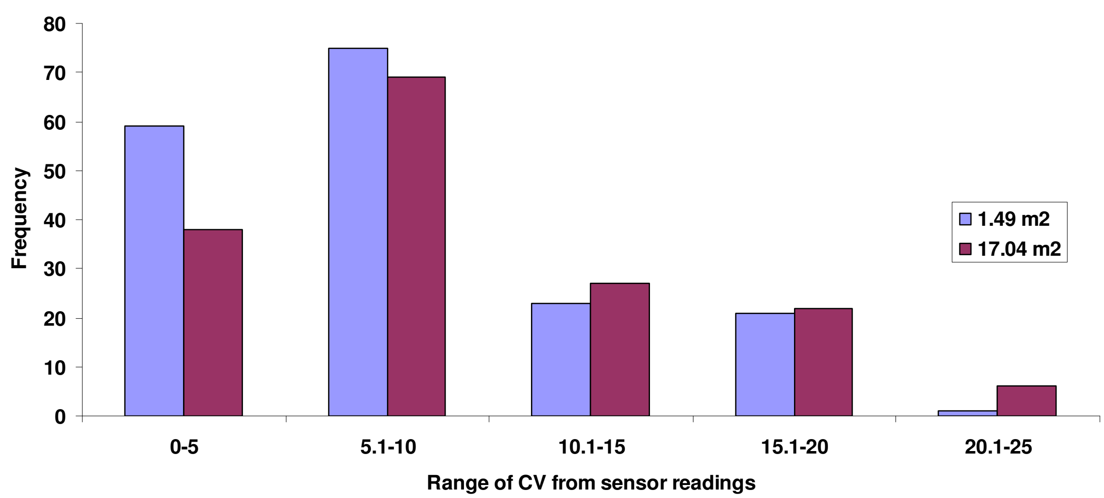

Figure 20. Distribution frequency for the CV of NDVI readings taken from plots used for RI analysis, where the majority of the samples had a CV of 5.1 to 10.0.

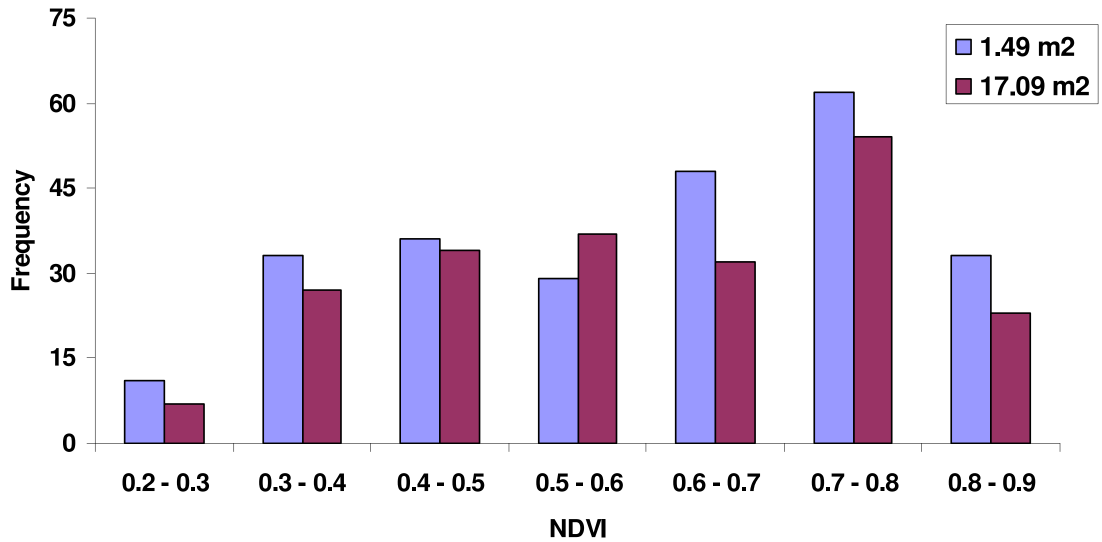

Figure 21. Distribution frequency for the NDVI readings taken from plots used for RI analysis, where the highest occurance of the samples had a NDVI of 0.7 to 0.8.

APPENDIX

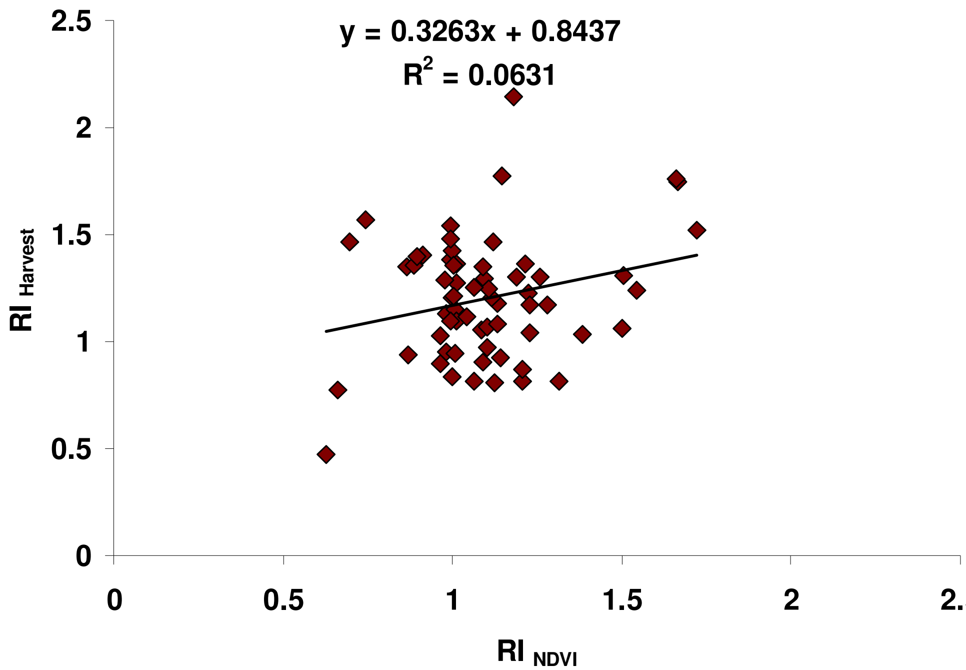

Figure A1. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from sub (1.49 m^2) plots receiving 44.84 kg N ha^{-1} plots collected at Feekes growth stage 6.

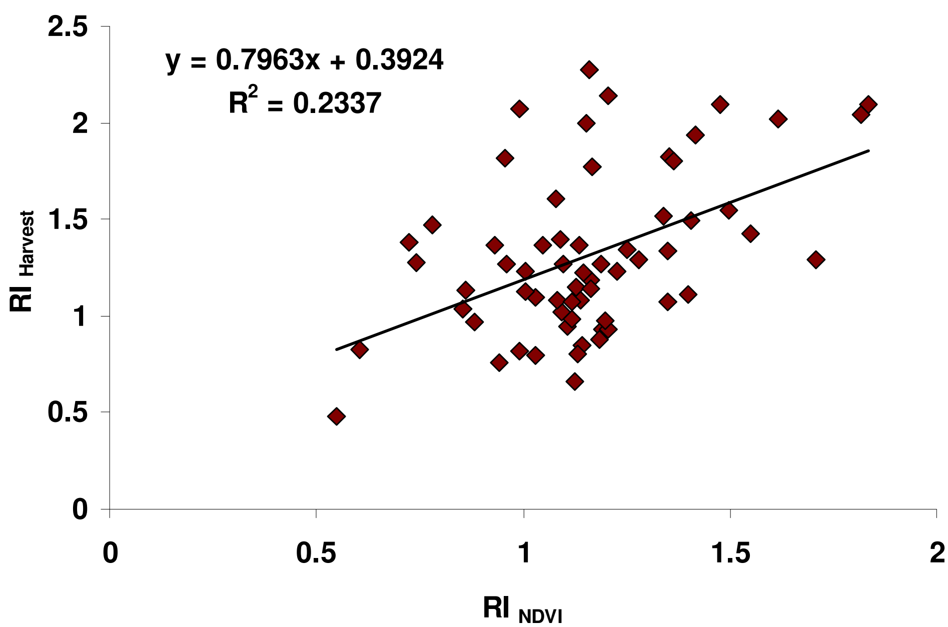

Figure A2. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from sub (1.49 m^2) plots receiving 89.68 kg N ha^{-1} plots collected at Feekes growth stage 6.

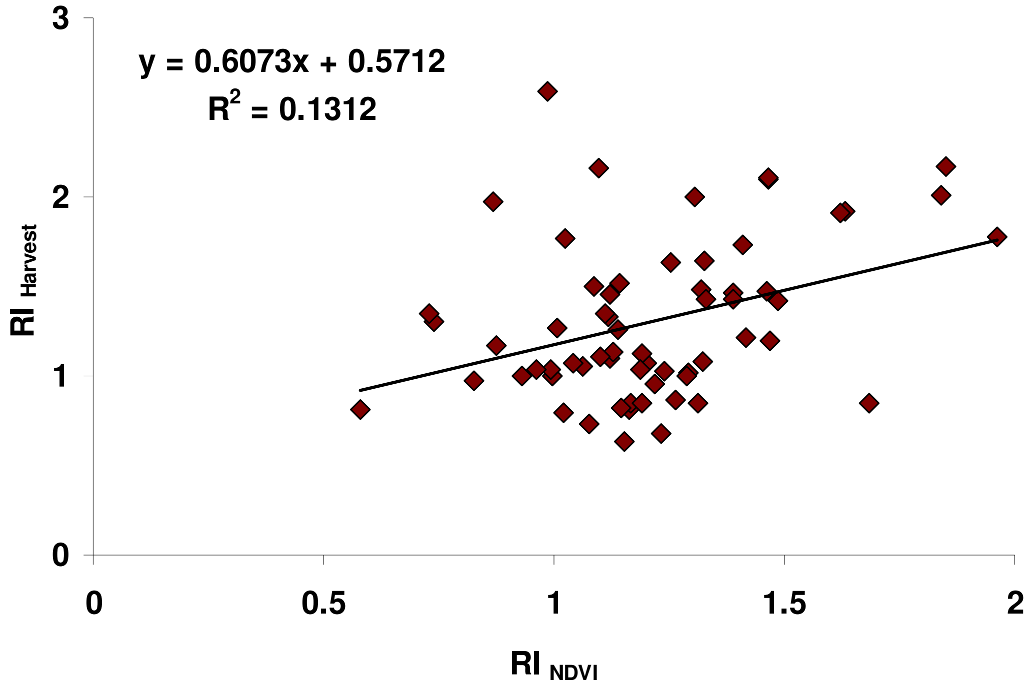

Figure A3. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from sub (1.49 m^2) plots receiving 134.52 kg N ha^{-1} plots collected at Feekes growth stage 6.

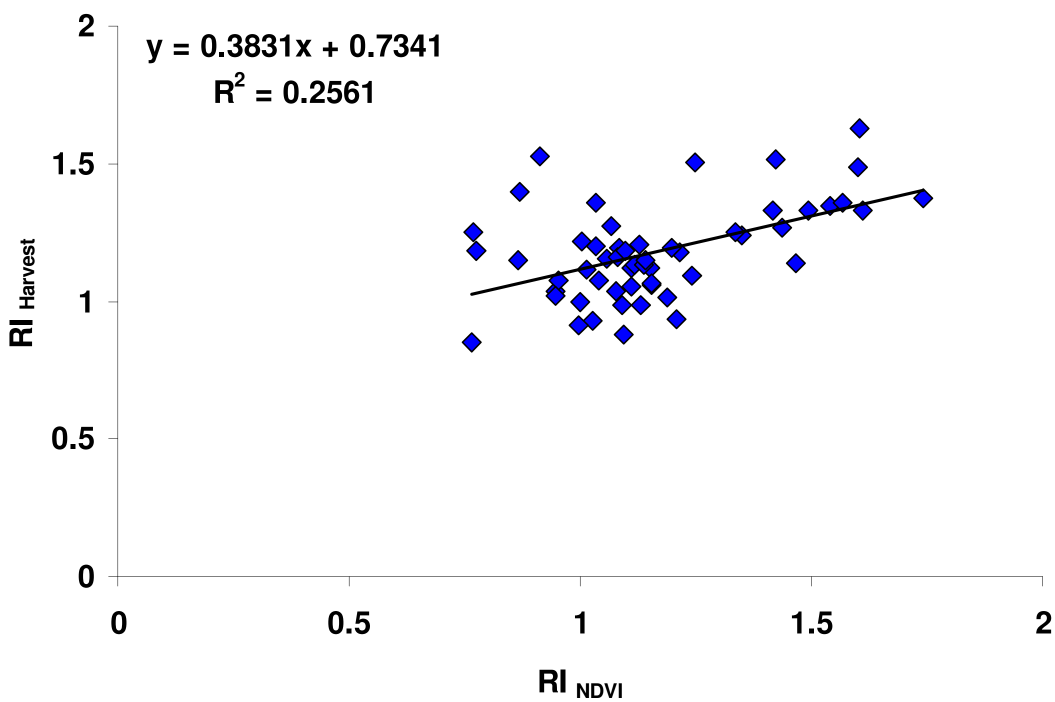

Figure A4. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from large (17.09 m^2) plots receiving 44.84 kg N ha^{-1} plots collected at Feekes growth stage 6.

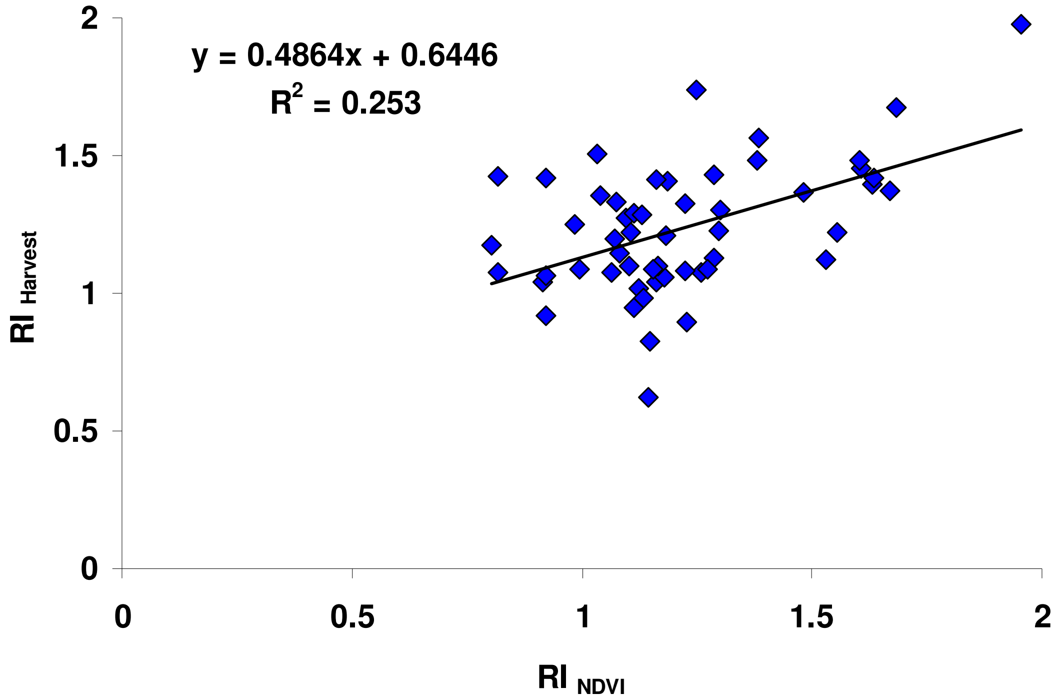

Figure A5. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from large (17.09 m^2) plots receiving 89.68 kg N ha^{-1} plots collected at Feekes growth stage 6.

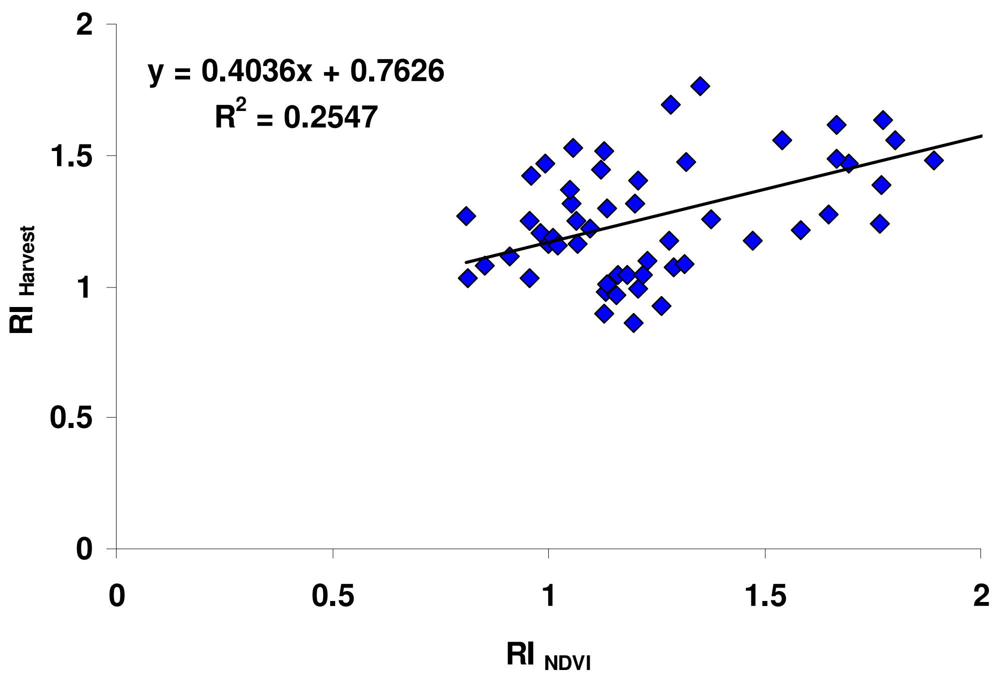

Figure A6. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from large (17.09 m^2) plots receiving 134.52 kg N ha^{-1} plots collected at Feekes growth stage 6.

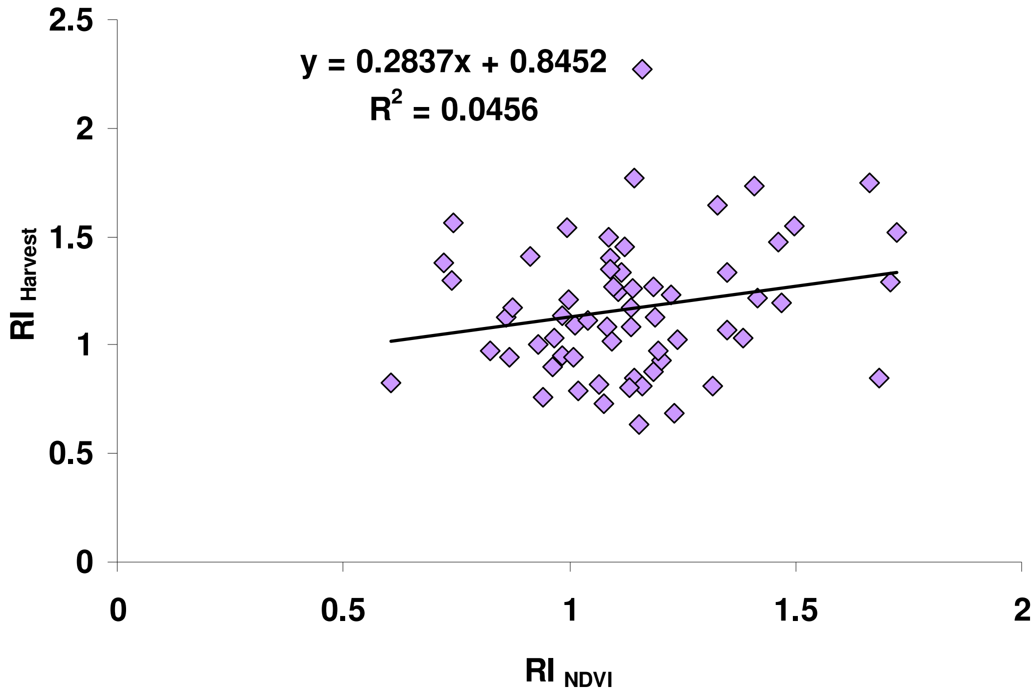

Figure A7. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from large (17.09 m^2) plots receiving 44.84 kg seed ha^{-1} plots collected at Feekes growth stage 6.

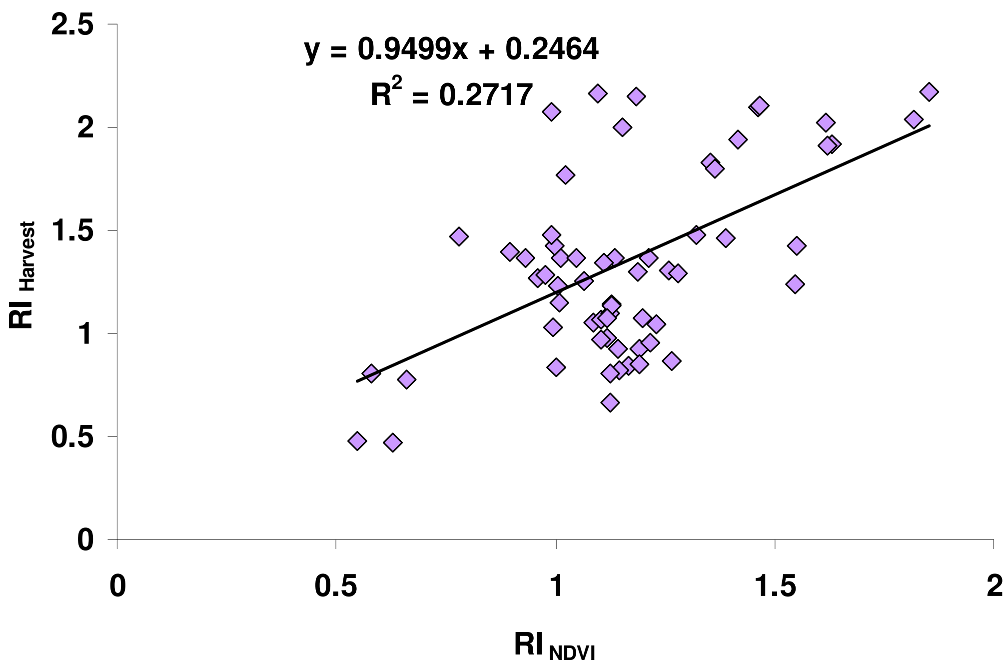

Figure A8. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from sub (1.49 m^2) plots receiving 89.68 kg seed ha^{-1} plots collected at Feekes growth stage 6.

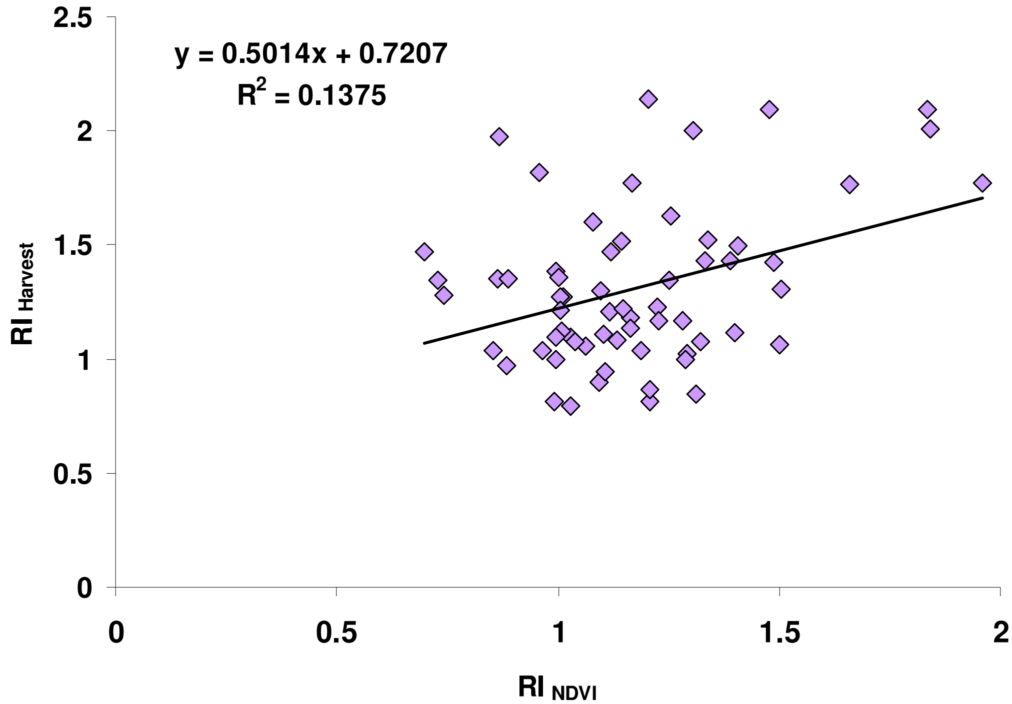

Figure A9. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from sub (1.49 m^2) plots receiving 134.52 kg seed ha^{-1} plots collected at Feekes growth stage 6.

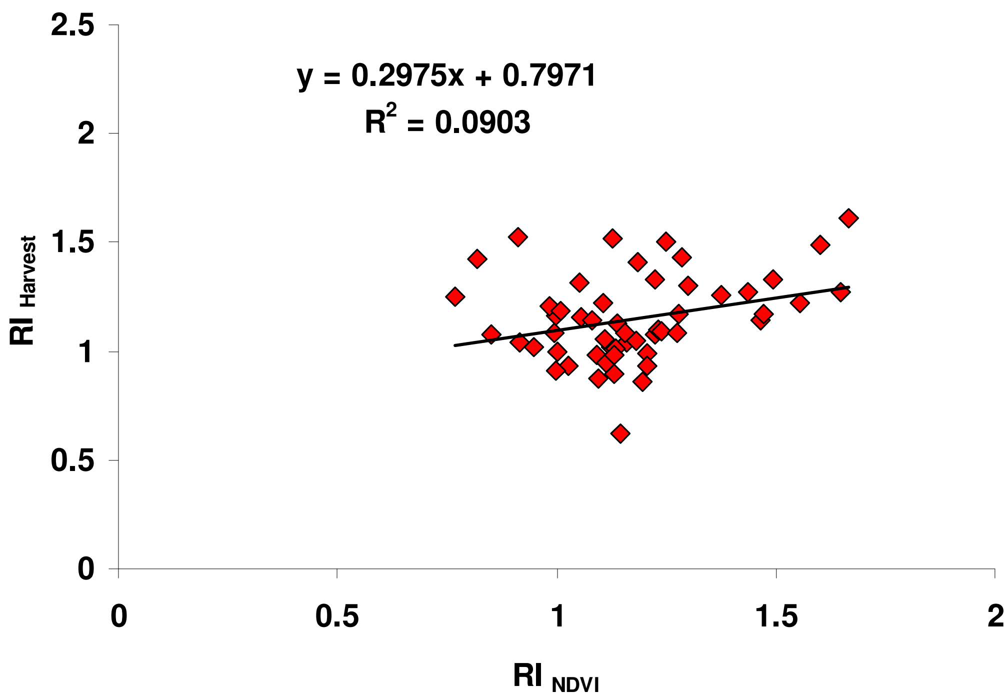

Figure A10. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from large (17.09 m^2) plots receiving 44.84 kg seed ha^{-1} plots collected at Feekes growth stage 6.

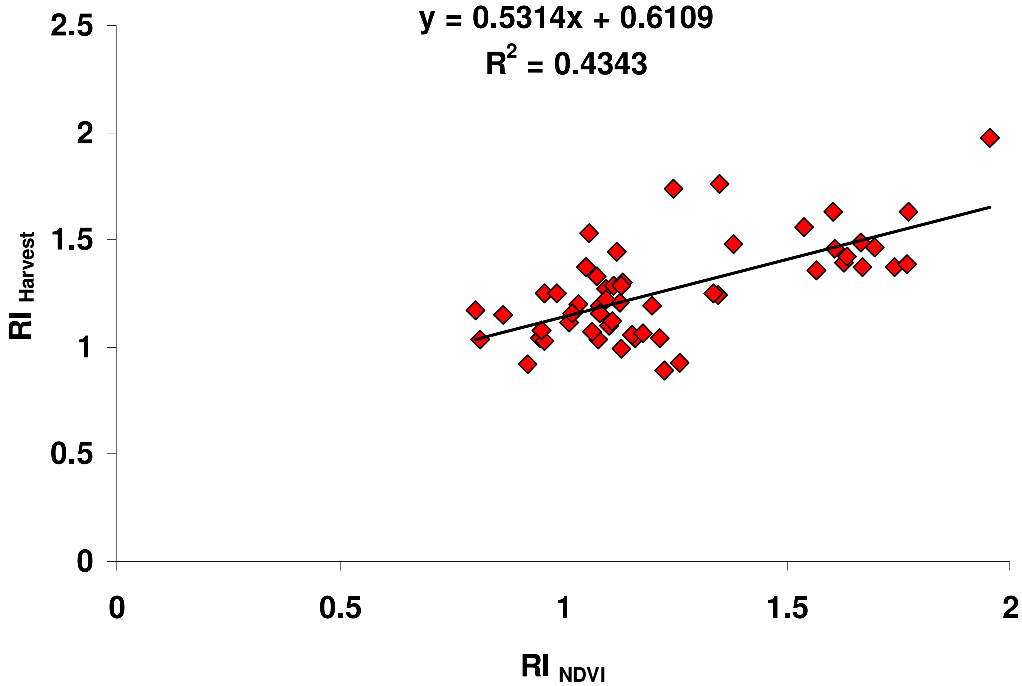

Figure A11. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from large (17.09 m^2) plots receiving 89.68 kg seed ha^{-1} plots collected at Feekes growth stage 6.

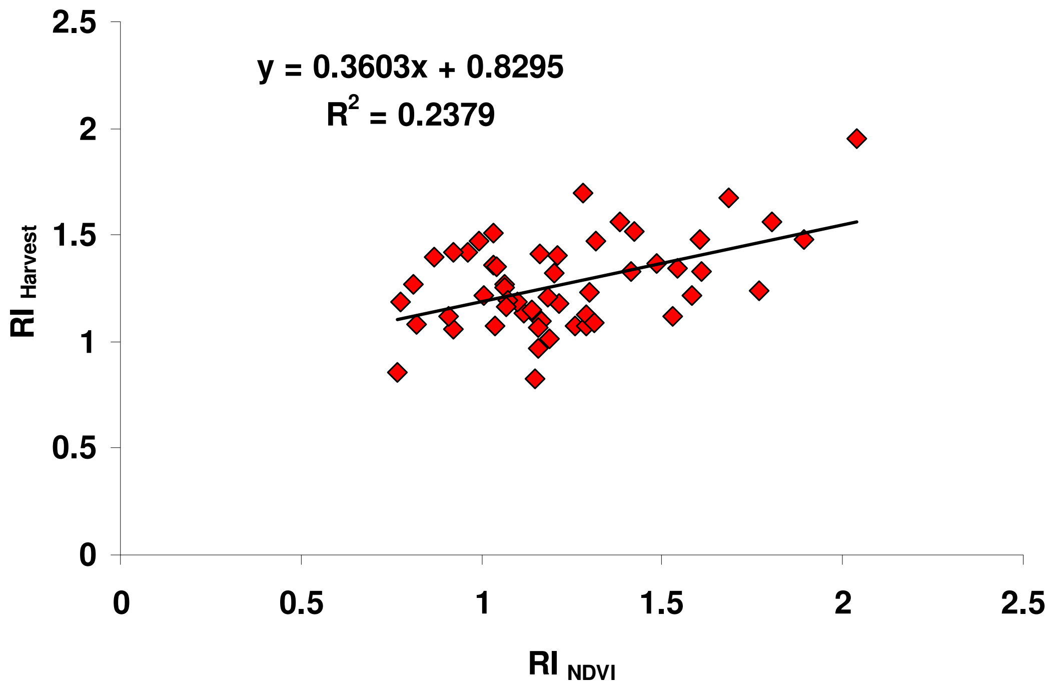

Figure A12. Relationship between $RI_{Harvest}$ (yield of fertilized plot / yield of control) and RI_{NDVI} (NDVI of the fertilized plot / NDVI of the control) from large (17.09 m^2) plots receiving 134.52 kg seed ha^{-1} plots collected at Feekes growth stage 6.

DEVELOPMENT OF A YIELD PREDICTION MODEL TO BE USED FOR THE MID-SEASON NITROGEN RECOMMENDATION OF COTTON *GOSSYPIUM HIRSUTUM* L..

ABSTRACT

The use of remote sensors to determine mid-season nitrogen (N) rates in cereal grain production has made great advances in the past five years and is gaining acceptance by producers. Sensor technology has yet to be used in cotton production, primarily due to differences in cultural practices between the crops. Cereal grain producers have historically applied excess nitrogen fertilizer because it lowered the risk of yield loss. While the price of fertilizer was low it only took a small increase in yield to off set the extra cost, therefore producers viewed over application as a method of reducing risk. However, over application of N in cotton leads to excessive growth and the need to apply growth regulators. Alternatively under application of N can result in a dramatic decrease in yield. This study was designed to 1) develop a sensor based yield prediction model using normalized difference vegetative index (NDVI) readings from an optical sensor, 2) incorporate the new yield prediction model into an algorithm used to determine mid-season application of N in cotton, and 3) to predict N response in terms of final lint yield using RI_{NDVI} (NDVI in the fertilized plot divided

by NDVI in the unfertilized check). Two nitrogen rate field trials were used for the data collection, Lake Carl Blackwell Nitrogen Study and the Altus Nitrogen Rate Study. Sensor readings were collected with a Green Seeker™ RT 500 and hand held sensors throughout the growing season. The NDVI readings taken during the season between 60 and 80 days after planting were highly correlated with final yield. The prediction of final yield was improved when NDVI was divided by the cumulative growing degree day units that were measured between planting and sensing (CumGDD INSEY), when the sensor readings where collected between the growth stages of square growth mid point and peak bloom. The relationship between the response in final lint yield to added N fertilizer and the response measured mid-season with NDVI values during the period of 60 to 80 days after planting, resulted in an r^2 of = 0.38. Also recorded was the trend for NDVI to increase with time to the point of about 80 days after planting. Beyond this time, yield prediction was not possible since the canopy was at or near closure. This study showed that yield potential in cotton could be accurately predicted in-season using NDVI, which confirms that there is a great potential for the use of sensor based N rate recommendations in cotton

INTRODUCTION

Precision farming includes the use of technologies to map yield variability within a field and diagnose the causes of variability, prescribe variable rates of inputs across the field according to soil and crop needs, and apply those inputs at variable rates according to the prescription (Roberts et al., 2002). Johnson et al., (2002) termed precision agriculture as information and technology based agricultural management systems that analyze, identify, and manage site spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment. The goal of such technologies is to reduce input levels and produce a more homogenous product. To produce homogeneity, all factors influencing yield and quality of the final product must be controlled.

Cotton (*Gossypium hirsutum* L.) yield is influenced by many factors. Climatic factors such as moisture availability, length of growing season, and temperature extremes affect yield. Other sources of variability include soil type, soil moisture, pH, fertility levels, organic matter, weed pressure, insect pressure, growth regulators, crop termination, and wildlife damage (Meredith, 1996; Wilkerson, 1996). Significant variation in cotton yield has been reported to occur at distances as short as 10 m, suggesting that a modification of current soil- and plant-sampling schemes might prove necessary and more appropriate for precision agriculture applications (Johnson et al., 2002).

Precision farming is not a new term in the world of cotton production. Precision farming has many different meanings and over time has moved in multiple directions. In the 90's it was reported that developments in cotton yield-sensing technology (Wilkerson, 1996) and soil-fertility mapping (Valco, 1998) showed potential for widespread use in cotton production. Precision agriculture in many forms has the ability to offer cotton producers management tools and strategies that could help to control production inputs so that return is maximized. Although absolute quantities of crop inputs may not be decreased, the reallocation of these inputs could result in better utilization and decreased waste (Olson, 1998). Alluding to the temporal variability in crop needs, some years a reduction of inputs is called for while in other years an increase is needed to reach maximum yields (Girma et al., 2007b; Machado et al., 2002; Mamo et al., 2003a; Mullen et al., 2003). Long term total inputs are projected to not decrease but the efficiency at which they are used will increase.

Current Nitrogen Management Practices

Yield Goals

Cotton nitrogen recommendations are determined using yield goals are based on estimating crop removal of N. Cotton Incorporated (www.cottoninc.com) explains that the total quantity of N required can be estimated by; 1) estimating yield in kg per ha 2) divide by 217.9 kg/ bale and 3) multiply by 22.7-25.0 kg N /bale (Nichols and Green, 2008). This results in an estimate of kg of N in the crop. Once this value is attained, the amount of N available has to be subtracted to reach a preplant N rate. At present, Cotton Incorporated suggests that available N can come from 5 sources: atmospheric deposition, N mineralized from soil organic matter, residual soil nitrate N measured in the spring prior to planting, N credits from preceding crops, and N derived from animal wastes and other organic amendments. The result of this is explained to be the minimum quantity of fertilizer N needed to ensure sufficient N to achieve the yield goal. Fertilization based on yield goals is a vast improvement over simply applying the same amount of N year after year, especially when credits and residual N are accounted for. However, this practice is limited since at the time of planting there is no way to accurately predict yield, even when using averages over the past few years as is the case with using yield goals. As a result, the use of yield goals can be inaccurate, because of the drastic effect environment has on final yield in virtually every production environment.

Petiole Analysis

Petiole monitoring has provided producers the ability to track in-season N conditions of the crop. Many universities are recommending the use of petiole nitrate levels as a monitoring and management tool (Ayala and Doerge, 2001; Hickey et al., 1996; Wright et al., 2003). Petiole nitrate-N was shown to be well correlated with the N balance of the previous crop, N uptake, and lint yield of unfertilized cotton (Rochester et al., 2001). Rochester et al. (2001) observed that the economic optimum N rate was closely correlated with soil and petiole nitrate results. The conclusions of this study was that the combination of soil and petiole nitrate analysis can provide proper guides to what would likely be the supply of N to the crop following legumes. Keisling et al. (1995) concluded that the petiole nitrate N content by itself is useful for determining the N status and needs of the crop until the third week of bloom.

Unfortunately a shortcoming of petiole nitrate analysis has been stated by many. The downfall of the test is that it estimates flow of nitrate from the root to the leaf with the transpiration stream, and the petiole test is hypersensitive. This sensitivity can often vary with cultivar, growth stage, soil type, weather and insect damage, which causes the test results to be quite difficult to interpret (Heitholt, 1994; Keisling et al., 1995; Maples et al., 1990; Sabbe and Zelinski., 1990).

Timing of Nitrogen Uptake and Application

The most efficient method in which to supply N to any plant is to have N in place only at the time when the plant is in need, is well accepted. Therefore, it is very important when discussing the timing of N application that the timing of N uptake in the plant is also known. Boquet and Breitenbeck (2000) observed a maximum N uptake of 2.9 to 4.3 kg ha^{-1} occurring during the period of 49 to 71 days from planting (DFP) for cotton receiving 84 and 168 kg N ha^{-1}, respectively. Maximum uptake was recorded between early square and early bloom in both

Acala and Pima cotton by Fritschi et al. (2004a).

The environment also has to be considered when making fertilizer timing decisions. For conditions where N losses are more likely, split applications of N can be more beneficial. Mullins et al. (2003) suggested that when leaching potentials are great on sandy soils of the Coastal Plain, N should be split applied in at least two if not more applications. When ammonium nitrate was applied at multiple times during the crop cycle, no differences in lint yield were observed, N application at first square produced the highest yield, and two of the years the N applied preplant was adequate (Mullins et al., 2003). Additionally, in a study that reviewed the application of foliar N based on weeks after white flower or nodes above white flower, additional fertilizer N was found to be beneficial to the crop regardless of soil N levels (Bondada et al., 1999).

A four year study in Florida found that the optimum time to apply N is at first square. The results suggested that on heavier soils only one sidedress application was needed however, on sandier soils two N applications sufficed, at squaring and at first bloom (Wright et al., 2003).

Sensor Based Nitrogen Management

Including sensor based nitrogen management into modern cotton production has many more challenges than does its adoption into small grain production. In grain production, more biomass lends itself to higher yields, and excess N fertilization only leads to the loss of nitrogen with few negative impacts on yield. In cotton production systems, this is not the case. When a cotton crop has excessive amounts of soil N and the proper environmental conditions are present, excessive vegetative or “rank growth” can occur. Excessive vegetative growth can reduce yields and lint quality (Hearn, 1986; Singh et al., 1989). If nitrogen can be supplied to the crop only when it is needed, the probability of having excessive growth or nitrogen loss to the environment would be reduced. The degree of variability observed in cotton yields suggests that precision agriculture techniques could provide effective management strategies for maximizing fiber yield and quality. Possible techniques would include variable-rate fertilizer application and selective harvest (Elms et al., 2001). Crop N requirements have been reported to be highly variable in the southeastern USA, with a range from 67 to 255 kg N ha^{-1} (Boquet et al., 1993). It is also widely recognized that variation occurs within all agricultural fields (Elms et al., 2001; Johnson et al., 2002; LaRuffa et al., 2001; Mamo et al., 2003b; Meredith, 1996; Rockstrom et al., 1999; Solie et al., 1999; Washmon et al., 2002; Zarco-Tejada et al., 2005). The use of an optical sensor may be the most accurate method of differentiating nitrogen stress levels and differences in yield potential (Elms et al., 2001).

Optical Sensors and NDVI

Read et al. (2002) noted that as the N deficiency in cotton decreases, chlorophyll (Chl) content (Longstreth and Nobel, 1980), and the rate of leaf expansion and canopy development also decrease (Gerik et al., 1998; Reddy et al., 1997). With this in mind the authors concluded that remote sensing of Chl has the potential to quickly estimate cotton N status and therefore crop productivity (Read et al., 2002). Nitrogen fertilizer levels and SPAD meter readings held a highly significant linear regression before boll opening (Feibo et al., 1998). Using SPAD readings, Feibo et al. (1998) developed a critical level for early flowering, flowering peak, boll forming, the beginning of boll opening and open boll stages. The final recommendation was a 24.2-25.0 kg ha^{-1} increase in N rate for each unit of decrease in SPAD value below the determined critical level.

The GreenSeeker™ optical sensor is an active sensor that emits two bands of light, red and NIR, and measures the amount of reflectance. The value reported from this measurement is the indices termed Normalized Difference Vegetative Index (NDVI). NDVI has been shown to be a good estimator of total plant biomass (Freeman et al., 2003; Raun et al., 2001; Raun et al., 2002). The sensor works because plants with more leaf area and chlorophyll absorb higher levels of red light; conversely, healthy plants are able to reflect more NIR than less healthy plants. The ratio of the level of reflectance of red and NIR are highly useful when using NDVI as an indirect measure of plant health. Although the GreenSeeker™ sensor has yet to be thoroughly tested in cotton, Sui and Thomasson (2004) found that NIR and red wavelengths had strong correlation with cotton leaf N content. NDVI has been shown to record the typical pattern of the cotton crop where during the early season the canopy fills and then declines during later in the season as the vegetation senesces (Plant et al., 2000). Plant et al. (2000) reported that lint yield was correlated with NDVI but only in those cases where the effect of N was very significant. Also observed was a potential for NDVI to give a false positive indication of yield loss, because NDVI was able to indicate the presence of N stress in the cases where the deficiency did not result in a reduction of final yield. In the Plant et al. (2000) study, NDVI was highly correlated with nodes above cracked boll and correlated with nodes above white flower.

Nitrogen Fertilization Optimization Algorithm

Using a non-limiting N reference strip applied in the field at planting, and a handheld spectral reflectance sensor, producers can prescribe N rates for their fields that account for residual soil N and the influence of the environment. The N rate is calculated using several steps and is referred to as the Nitrogen Fertilization Optimization Algorithm (NFOA), which was originally outlined by (Lukina et al., 2001).

The NFOA utilizes four primary components:

1. **Yield Prediction Model (YP)**
2. **Response Index (RI)**
3. **Nitrogen Removal (%N)**
4. **Nitrogen Use Efficiency (NUE)**

Yield Potential

The yield potential (YP) of many small grain crops, including winter wheat, spring wheat, corn, and rice, has been shown to be predictable mid-season (Lukina et al., 2001; Raun et al., 2001; Raun et al., 2002; Raun et al., 2005; Teal et al., 2006). Winter wheat grain yield potential can be predicted using an in season estimate of yield or INSEY, which is calculated by taking NDVI, divided by the number of days from planting to sensing where growing degree days (GDD) ((Tmin + Tmax)/2 – 4.4℃) were more than zero. For summer crops such as cotton, the average temperature where growth takes place is higher (>10℃), so the computation of INSEY can be NDVI divided by the number of days from planting to sensing for summer crops and that results in an index that is essentially biomass produced per day. Or the index can be computed by dividing NDVI by cumulative GDD's which would be biomass produced per cumulative heat units. Either method of computing INSEY provides an estimate of crop growth rate. Correlation between biomass produced per day and final grain yield has been shown to be quite good (Raun et al., 2001). Knowing mid-season what a crop can potentially produce as final harvestable yield can have many implications on the normal practices commonly performed mid-season. The ability to determine yield potential of a crop mid-season is the most important component of the NFOA and the sensor based nitrogen rate calculator (SBNRC) which is a user friendly program that utilizes the NFOA to make N rate recommendations for many crops and regions and that producers are using.

Response Index

The Response Index (RI), was described by (Johnson and Raun, 2003) as the response in yield to additional fertilizer nitrogen, calculated by dividing the yield of the high nitrogen plot or reference strip by the yield of the 0 N plot or farmers practice where less preplant N was applied. The RI value calculated using yield is referred to as $RI_{HARVEST}$. Response Index can be measured mid-season using NDVI values collected from active sensors, RI_{NDVI} from the exact same plots, but early in the season. It has been shown that RI_{NDVI} collected during vegetative stages is a good predictor of $RI_{HARVEST}$ (Hodgen et al., 2005; Mullen et al., 2003). This means that the response, in terms of yield, due to the addition of fertilizer nitrogen can be determined at the time topdress fertilizer is applied.

Nitrogen Concentration and Use Efficiency

Nitrogen rate recommendations for cotton production revolve around yield goals. For all cotton production areas the basic calculation for N rate encumbers, X kg of N for every unit of yield expected. The rate for every bale of lint produced ranges from 56-67 kg depending on region or state. Research has shown from 100 to 200 g of N was removed from the soil for every 1.0 kg lint yield (Bassett et al., 1970; Mullins and Burmester, 1990; Unruh and Silvertooth, 1996). Janat (2005) found that under low N input conditions, 60 g N was taken up for every 1 kg of seed cotton and there was 79.0 g N removed under high input conditions. These values translate into approximately 180.0 g and 237.0 g N per 1 kg of lint.

To determine N removed per unit of yield, the components of yield and their N concentrations must be understood. In a study that partitioned N concentrations in the aboveground biomass at the time of defoliation of both Pima and Acala cotton, Fritschi et al. (2004b) recorded 18.8 g N kg^{-1} in leaves, 8.6 g N kg^{-1} in stems, 15.2 g N kg^{-1} in burs, 52.0 g N kg^{-1} in seed, and 5.4 g N kg^{-}

^{1} in fiber in Pima and 21.0 g N kg^{-1} in leaves, 11.1 g N kg^{-1} in stems, 8.8 g N kg^{-1} in burs, 55.4 g N kg^{-1} in seed, and 3.7 g N kg^{-1} in fiber for Acala. The results were the averages across all treatments and years. Nitrogen concentration recorded in the seed was 24.9-31.9 g N kg^{-1} and 32.7-42.5 g N kg^{-1} for Pima and Acala respectively. The lint N ranged from 2.7-3.1 g N kg^{-1} for Pima and 2.4-3.6 g N kg^{-1} in Acala (Janat, 2005). Similarly, Boquet and Breitenbeck, (2000), reported N concentration in the seed of 33-43 g N kg^{-1}, lint of 2.2-2.9 g N kg^{-1}, carpel of 10-22 g N kg^{-1}, with the boll as a whole unit containing a total 16-25 g N kg^{-1}.

Boquet and Breitenbeck (2000), preformed an in-depth analysis of how N is partitioned in dry matter of cotton at multiple N rates. When cotton was sampled during effective bloom at the optimum N rate (84 kg N ha^{-1}), 51% of the N was found in the branches and stems, 19% in the leaves, and 25% in the bolls. At maturity the harvest index of both the optimum and zero N rates was 32%. At harvest for the 84 kg N ha^{-1} rate, seedcotton contained 43% of the total assimilated N. For each kg of seedcotton produced at this rate, the crop assimilated 52 g of N of which 22 g was partitioned to harvested seedcotton. In this study the total seasonal N uptake from the optimum N rate was 235 kg ha^{-1}, of which 42 to 49% was removed from the field at harvest (Boquet and Breitenbeck, 2000). Others have also shown that seedcotton on average contained 42% of the total N that was assimilated into the crop (Halevy, 1976; Mullins and Burmester, 1990; Oosterhuis et al., 1983).

The observation that the amount of N applied is not equal to the amount of N that is taken up has been well recorded. By using the values of N applied and N removed in grain cereal crops world wide, Raun and Johnson (1999) estimated that NUE was near 33%. Across the cotton belt researchers have cited NUE's ranging from 25% to 60% (Bassett et al., 1970; Fritschi et al., 2004a; Fritschi et al., 2004b; Hou et al., 2007; Janat, 2005; Unruh and Silvertooth, 1996). These reports come from a wide range of cotton varieties, soil types, environmental zones, timing regiments, and differing cultural practices. Mahmood et al. (2000) found that 39.3% of the total fertilizer applied was utilized by the crop with 19.2% being found in the soil after harvest. In this study, 77% of the fertilizer N recovered in the crop was found in the shoot with 19% and 4% of the fertilizer found in the seeds and roots, respectively.

When the results from the cotton research was compared to similar studies preformed under irrigated maize and wheat cropping systems in the same area (Mahmood et al., 1998), fertilizer loss under cotton was the same as maize at 39% and only slightly higher than that of wheat at 33% (Mahmood et al., 2000).

Nitrogen Rate Calculation

Raun et al., (2002), reported that with the combined use of the RI concept and mid season prediction of yield, INSEY, an accurate topdress nitrogen rate can be made. This is essentially done by predicting the yield of an area that represents the "farmer practice." Then, by multiplying the response index

(RINDVI) times the farmer practice potential yield or YP0, the yield obtainable with added fertilizer or YPN is determined. The fertilizer N rate is the difference in estimated N uptake at YPN and YP0, divided by an expected or theoretical efficiency factor, ranging between 0.5 and 0.7 (Raun et al., 2005).

The four components of the NFOA previously reviewed are placed into an algorithm as follows:

N Rate = (YP0 * RI – YP0) * %N / NUE

HYPOTHESIS AND OBJECTIVES

The hypothesis of this study is that using the GreenSeeker™ hand held sensors a mid-season nitrogen rate recommendation can be developed for cotton. This will involve the development of a specialized algorithm based on estimated N responsiveness, and yield prediction. The objectives of this study were to build a yield potential prediction model, and to record the relationship between $RI_{Harvest}$ and RI_{NDVI}. Using this information, a Nitrogen Fertilization Optimization Algorithm (NFOA) will be created using the YP model and RI prediction.

MATERIALS AND METHODS

One experimental site was established in the spring of 2006 near Stillwater, OK at the Lake Carl Blackwell Agronomy Research Farm (LCB). Two years of data from 2006-2007, was collected from this site. During 2007 data were also collected from an N rate study near Altus, OK at the South West Research Station (SWR).

The two sites, LCB and SWR are both irrigated. The LCB site is irrigated through a T&L lateral roll sprinkler system and the SWR is furrow irrigated. Soil characteristics of the two sites are described in Table 1, and initial soil test results are reported in Table 2.

The experimental design of the LCB trial consisted of fifteen N treatments in a randomized complete block design with three replications. Plots consisted of four rows with a total measurement of 3.05 m x 6.10 m. The treatment structure is shown in Table 3. Treatments consisted of all N applied preplant, all N applied sidedress, and a split application of N. Treatments that only received preplant N (trts 1-5, 14-15) were utilized for the prediction model.

The experimental design of the N rate study at the SWR was a randomized complete block with four replications. Four rates of N were evaluated and the treatment structure is reported in Table 4. All treatments were analyzed and used for generating a yield prediction model. All treatments were broadcast on the surface and incorporated prior to planting using urea (46-0-0), and irrigation was applied as needed from the Lugert Altus Irrigation District with amounts varying from year to year. Since the irrigation water was furrow applied, the amount applied per irrigation was approximately 50 to 60 mm.

At LCB in the spring of 2006, preplant N treatments were applied using urea (46-0-0) as the N source. For 2007, preplant N applications used liquid UAN (28-0-0) as the source of N. All sidedress N treatments were applied using liquid UAN dribbled along the base of each row.

The LCB site was planted in 76 cm row spacing and the SWR was planted in 102 cm row spacing. The 2006 and 2007 crop year planting data, seed variety, planting population and tillage practice are reported in Table 5. Pendimethalin (Prowl H_20, BASF Corporation) was applied preemergence at a rate of 2335 ml ha^{-1}. Glyphosate was applied as needed during the growing season at a rate of 3502 ml ha^{-1}per application. Also, recommended rates of growth regulators, fungicides, and insecticides were applied each year.

Plots at LCB and SWR were monitored once a week after the crop reached a height of 45 cm. All measurements were collected from the center two rows of each plot. Plots were sensed with a GreenSeeker™ hand held optical reflectance sensor (NTech Industries, Ukiah, CA), measuring NDVI with the sensor approximately 70 cm directly above the crop canopy. Canopy height was collected at LCB using meter sticks to record the distance from the ground to the top of the canopy at 10 randomly selected locations within a plot at the same time when sensor readings were collected. Table 6, reports the day from planting to sensing (DFP), Cumulative GDD (CumGDD) and growth stage at the time each trial was sensed.

Each year at both locations defoliants and a harvest aid were applied to facilitate harvesting. At maturity the two middle rows were harvested. In 2006 and 2007 LCB was harvested by hand picking the two middle rows of each plot. After harvest the lint was pulled from bolls and weighed. The plots at SWR were mechanically harvested with a commercial cotton striper. Grab samples were collected from the harvested material in each plot and ginned on small ginning equipment in order to approximate lint turn out and ginning percentage.

The indices of NDVI which was the value collected by the GreenSeeker™ sensor is computed as:

$$NDVI = \frac{\rho_{NIR} - \rho_{\text{Red}}}{\rho_{NIR} + \rho_{\text{Red}}}$$

Where: ρ_{NIR} fraction of emitted NIR radiation returned from the sensed area (reflectance)

ρ_{Red} fraction of emitted red radiation returned from the sensed area (reflectance)

Two different calculations for INSEY were made. One based on days from planting to sensing (DFP INSEY) for yield potential similar to Raun et al. (2002) and Teal et al. (2006). The second INSEY calculation was based upon cumulative GDD's (CumGDD INSEY), as outlined in Teal et al. (2006), as a predictive lint yield model.

The days from planting to sensing INSEY (DFP INSEY) (Teal et al., 2006) was calculated as:

$$DFP\ INSEY = \frac{NDVI}{DFP}$$

Where: $DFP -$ days from planting to sensing

In addition, the cumulative growing degree days INSEY (CumGDD INSEY) was calculated as:

$$CumGDD\ INSEY = \frac{NDVI}{GDD}$$

Where: *Cum*GDD- cumulative growing degree days (CumGDD) from planting to sensing and calculated using the "optimum day method" (Barger, 1969)

$$GDD = \frac{T\max + T\min}{2} - 60\ ºF$$

Where: 60º F and 100º F minimum and maximum temperatures, respectively.

Also, the yield potential + one standard deviation method (Raun et al., 2005) was utilized to develop an accurate measurement of yield potential, YP0.

RI_{NDVI} was calculated by dividing the mean NDVI of an N treatment by the mean NDVI value of the check treatment. $RI_{HARVEST}$ was calculated by dividing the each N treated plot yield by the check plot yield from the same rep.

All statistical data analyses were performed using the General Linear Model (GLM), Regression (REG) and Mixed (MIXED) procedures, linear and non-linear regression models were used to determine the relationships present between lint yield and the multiple indices created using procedures in SAS (SAS Institute, 2007).

RESULTS

The relationship between readings collected using a hand-held GreenSeeker™ sensor at early growth stages in cotton and final lint yield is reported in Figure 1. This relationship showed very little correlation between NDVI and lint yield when collected from a wide range of growth stages, early vegetative to undeveloped boll (r^2 = 0.25). The relationship between DFP INSEY determined by dividing NDVI by the number of days from planting to sensing and final lint yield when measured over a range of growth stages is illustrated in Figure 2. This relationship also showed very poor correlation (r^2 = 0.05). The sensor readings were recorded over a period of time that ranged from 38 to 90 DFP. When CumGDD INSEY was used to predict final lint yield (Figure 3) the relationship was improved, r^2 = 0.38, ranges from 644-1568 cumulative GDD.

When the range of collected NDVI readings was narrowed from 60 to 80 DFP and then compared to final lint yield the relationship was improved, r^2 = 0.39 (Figure 4). The introduction of DFP utilized in INSEY assisted in predicting final yield, with an r^2 = 0.46 (Figure 5). The trend line that best fit the relationship between INSEY and final lint yield was an exponential equation just as it has been shown to be the case with the other crops where GreenSeeker™ has been utilized as an instrument to predict potential yield mid-season (Freeman et al., 2003, Raun et al., 2001). Teal et al. (2006) observed in corn production using

INSEY based on cumulative GDD's (Cum GDD), that prediction of final yield was equal to or better than that of INSEY based on DFP. In this study, the result of using Cum GDD resulted in a much better yield prediction model (Figure 6), r^2 = 0.69. The time period from which the data used for the model shifted because the range of DFP did not follow well with cumulative GDD. The range of 800 to 1300 cumulative GDD's corresponded to the growth stages of pinhead square to peak bloom. The equation for the line follows.

$$\textbf{cotton lint yield, kg ha}^{-1} = 177.41\ e^{2216.2 * INSEY}$$

This was the trend line that best fit the average of the combined values collected. Because the objective of this study was to develop a yield potential model, the line that is one standard deviation above the average was used, as outlined in Lukina et al., (2001). This equation was:

$$\textbf{potential cotton lint yield, kg ha}^{-1} = 235.96\ e^{2216.2 * INSEY}$$

The data set ranging from 60 to 80 DFP was selected because when sensor readings from 50-59 DFP were included in the yield prediction model, correlation with lint yield was greatly reduced, r^2 = .29 (Figure 7). Similarly, with later sensing dates (DFP > 80), the relationship between INSEY and yield was poorly correlated (Figure 8). This is because at this point in the crops growth (DFP > 80), NDVI ceased to increase while DFP was still increasing, and as DFP continued to increase NDVI began to decrease. The relationship between NDVI and DFP was best fit by a second order polynomial equation with an r^2 = 0.70 (Figure 9). Therefore INSEY shifted to the left as the number of days from planting to sensing increased and that is illustrated in Figure 8, where DFP INSEY was correlated with lint yield when data was collected after 80 DFP.

As Mullen et al. (2003) and Hodgen et al. (2005) observed in winter wheat, the relationship between $RI_{Harvest}$ calculated using final grain yield and RI_{NDVI} calculated with NDVI measurements in-season did not result in an equation with an intercept of zero and a slope of one. When the correlation between $RI_{Harvest}$ and RI_{NDVI} was explored, it was observed that when readings from all growth stages were included, the relationship between RI measured in-season that RI recorded at harvest was not highly correlated (r^2 =0.16, Figure 10). Although, when data that was collected before 60 DFP and after 80 DFP was removed, the relationship was dramatically improved, r^2 = 0.39 (Figure 11). The correlation observed can be expressed as a linear relationship where:

$$\mathbf{RI_{Harvest} = 1.8579 * RI_{NDVI} - 0.932}$$

Using the average N concentration reported (Boquet and Breitenbeck, 2000; Fritschi et al., 2004b; Janat, 2005) in the lint and seed, N removal values were determined. The average N found in seed was calculated to be 42.1 g N kg^{-1} and 3.0 g N kg^{-1} removed in the harvest lint. With an estimated harvest index of lint to seed in seed cotton set at 33%, the total N removed by the lint and seed for every kg of lint is 90.0 g. As Fritschi et al. (2004b) observed the seed and lint make up 59.1% of the total N removed by the crop with the remaining 40.9 % being captured in the burs, leaves, and stems. If these components are accounted for in the algorithm, this results in 146.4 g N kg^{-1} lint, which follows the Mullins et al. (1990) and Unruh and Silvertooth (1996) N removal results.

However, this is much higher than the values recorded as optimum N rates for cotton grown in Oklahoma (Girma et al., 2007a) of 83.0 g N kg^{-1} lint. The Girma et al. (2007a) data closely fit the value of 90 g N kg^{-1} lint which was calculated from the lint and seed values alone. The 90 g N kg^{-1} lint value will be used for the algorithm at this time instead of 146.4 g N kg^{-1} lint that includes the other plant components (lint, seed, burs, leaves, and stems) since this value is much higher than what was reported in the Girma et al. (2007a) work.

There was no consensus within the literature on cotton NUE. It was, however, discussed that soil type and climate play a significant role on expected NUE in cotton. The NUE levels recorded in the literature ranged from 25-60%. The NUE used for the Cotton NFOA will initially be established at 50%. This choice is because with the application of N being made at sidedress the NUE would be expected to be at the higher end of the recorded NUE range. Further research will be needed to refine this value.

With this, all the components needed to establish a NFOA have been presented and discussed. The cotton NFOA is as follows:

$$\mathbf{N\ Rate = (YP0 * RI - YP0) * \%N / NUE}$$

Where:

$$\mathbf{YP0 = 235.96\ e^{2216.2 * INSEY}}$$
$$\mathbf{RI = 1.8579 * RI_{NDVI} - 0.932}$$
$$\mathbf{\%N = 0.09}$$
$$\mathbf{NUE = 0.50}$$

DISSCUSION

The ability to predict potential yield is the central component of the cereal grain NFOA, and subsequently allows for correct prescription of mid-season N fertilizer rates. Cotton lint yield potential was accurately predicted using NDVI for the period between 60 and 80 days after planting. Normalizing NDVI with DFP or Cum GDD did improve the yield potential prediction. There was also good correlation between $RI_{Harvest}$ and RI_{NDVI}, suggesting that it is possible to predict the responsiveness to added fertilizer in terms of final yield, mid-season with NDVI. Combined, this allows for predicting the potential amount of N that will be removed in fertilized and non-fertilized plots. The difference in projected N uptake between the two is the recommended N rate prior to accounting for NUE. This same approach has worked very well for small grains. Now we have the formula for a fiber crop, and the next step is implementation. The only guarantee of the cotton NFOA is that it will evolve over time as more data is collected and theories explored, just as all other NFOAs developed by researchers at Oklahoma State University. At this time it is not known if using the N content of only the lint and seed is adequate or if it will be necessary to include the N contained in the burs, leaves or stems. Because the total percent N removed from the crop as harvested yield is lower in cotton when compared to grain crops, final estimates of N needed, will still need to be verified. In addition, the 50%

NUE used is at present a theoretical value, since NUE is known to be dependent upon the environment. Furthermore, the YP0 prediction equation will need to be refined with the addition of more sensor data, and from different cotton biotypes.

For sensor based N rate recommendations to be successful, the NFOA approaches, and theories involved must be thought of as dynamic and therefore changeable and adaptable to the situation and environment.

The future success of the NFOA and SBNRC depends on further research. A very important assumption of the SBNRC is that the crop can recover from early season N stress. The crop, (cereal grains or cotton), has to show a deficiency that can be detected using NDVI and then recover and produce maximum yields or near maximum yields after mid-season N fertilization. It is not known whether cotton as a crop will be able to do this. If cotton cannot completely recover from early season N stress this approach will not work. Wright at al. (2003) showed that with mid-season N, cotton can recover from slight deficiencies but cotton recovery from acute deficiencies is unknown and this is a problem that has to be addressed.

An additional discussion point hinges around cotton’s ability to go into excessive vegetative production when N is in excess and the environment is conducive to rapid growth. A potential problem that may be associated with the NFOA is directly related to the need to have reference strips. These high N strips will be the optimum environment for rank growth and the algorithm is using the NDVI values from the optimum area for the N rate recommendation. In this study, the conditions for excessive vegetative growth did not exist. So it will take future research to discover if the NFOA N recommendations will either avoid or create application levels that induce rank growth and if there will be a need to create N rate caps. These caps may be based upon NDVI value, maximum yield level, or a maximum N rate. The utilization of strategies such as the Ramp Calibration Strip (RSC) may well be the answer for this problem. The RCS is an extension of the N-rich strip that is in essence a small N rate study that can be easily placed into producer fields as a reference strip. If we are able to detect the potential for rank growth during the time of sidedressing within the ramp, a maximum rate can be determined. The potential also exists for future use of the RCS as an in season indicator of NUE; however more research is needed in this area.

As this approach is implemented in the online SBNRC it should be considered that the option to use either DFP or CumGDD is available. With the understanding that using CumGDD results in a more accurate yield prediction, but knowing that these values may not be available for all end users when DFP are easily calculated. The results from this research indicate that the use of sensor based mid-season N recommendations could have great potential in cotton production. The application of the correct N rate will not only benefit the producer and environment by reducing excessive N use, but also reduce the need for additional chemical application that helps the producer control the growth and more easily harvest the crop.

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Table 1. Soil series and description of Lake Carl Blackwell (LCB) and Altus South West Research Station (SWR) research locations.

Location	Soil Series	Description
LCB	Pulaski fine sandy loam	course-loamy, mixed, nonacid, thermic Typic Ustifluvent
SWR	Tillman clay loam	fine, mixed, superactive, thermic vertic Paleustoll

Table 2. Initial soil test results, 0 – 15cm, from composite samples collected before each trial was initiated.

Location	NH_4- N	NO_3- N	Soil Test P	Soil Test K	pH
	----------------------kg ha^{-1}--------------------------				
LCB	17.8	19.6	55.6	221.8	6.3

Table 3. Treatment structure for the LCB experimental site, 2006-2008.

Treatment	Pre-Plant	Top-dress	PIX application
	--------kg N ha^{-1}--------		
1	0	0	As Needed
2	50	0	As Needed
3	100	0	As Needed
4	150	0	As Needed
5	200	0	As Needed
6	0	50	As Needed
7	0	100	As Needed
8	0	150	As Needed
9	0	100	As Needed
10	0	150	As Needed
11	0	200	As Needed
12	0	25	As Needed
13	50	25	As Needed
14	50	0	Pix
15	200	0	No Pix

Pre-plant treatments applied using urea (46-0-0) or UAN (28-0-0) as the N source.
Top-dress treatments applied using liquid UAN (28-0-0) as the N source

Table 4. Treatment structure for the N rate cotton fertility study at the SWR experimental site.

Treatment	Nitrogen rate
	----kg ha^{-1}----
1	0
2	45
3	90
4	135

Nitrogen treatments applied using urea (46-0-0, NPK).

Table 5. Planting and seed bed information from the 2006 and 2007 crop years.

Location	Crop Year	Planting Date	Harvest Date	Variety	Population seeds ha^{-1}	Tillage
LCB	2006	5-15-2006	11-2-2006	**Monsanto NG 3273 B2RF**	52,000	Flat
LCB	2007	5-17-2007	12-5-2007	**Stoneville ST 6611 B2RF**	52,000	Flat
SWR	2007	5-18-2007	10-24-2007	**Stoneville ST 4554 B2F**	52,000	Beds

Table 6. The days from planting (DFP), cumulative growing degree days (Cum GDD), and growth stage of the crop for all sensing events.

Location	Year	Planting	Sensing	DFP*	Cum GDD**	Stage
LCB	2006	5/15/2006	6/20/2006	38	644	Vegetative
LCB	2006	5/15/2006	6/28/2006	45	767	Pin-head square
LCB	2006	5/15/2006	7/4/2006	51	886	Square growth mid point
LCB	2006	5/15/2006	7/8/2006	55	949	Candle - white bloom
LCB	2006	5/15/2006	7/17/2006	64	1161	Mid-Bloom
LCB	2006	5/15/2006	7/19/2006	66	1215	Peak Bloom
LCB	2006	5/15/2006	8/1/2006	79	1537	Boll (un developed cotyledon)
LCB	2007	5/17/2007	7/5/2007	50	646	Vegetative
LCB	2007	5/17/2007	7/11/2007	56	754	Pin-head square
LCB	2007	5/17/2007	7/25/2007	70	1015	Square growth mid point
LCB	2007	5/17/2007	8/1/2007	77	1152	Mid-Bloom
LCB	2007	5/17/2007	8/6/2007	82	1262	Peak Bloom
LCB	2007	5/17/2007	8/14/2007	90	1462	Boll (un developed cotyledon)
SWR	2007	5/18/2007	7/10/2007	52	846	NA
SWR	2007	5/18/2007	7/18/2007	60	999	NA
SWR	2007	5/18/2007	8/9/2007	81	1472	NA
SWR	2007	5/18/2007	8/13/2007	85	1568	NA

*DFP Days from planting to Sensing.
**Degree-day Calculator for Cotton: lower threshold 60°F, upper threshold 100°F

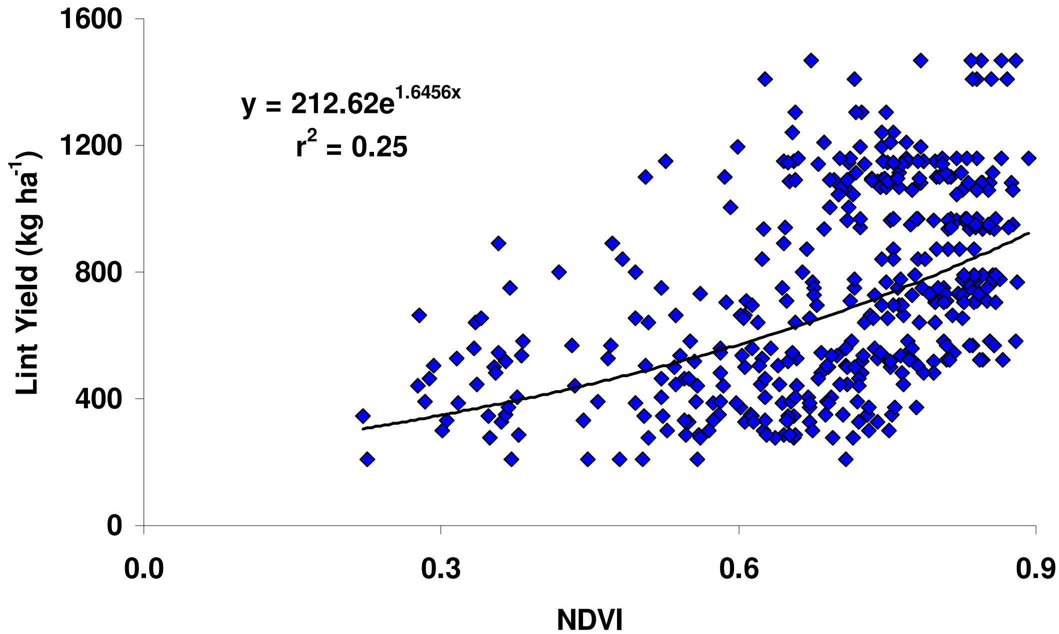

Figure 1. Relationship between the normalized difference vegetative index (NDVI) readings of cotton collected between 38 and 90 days after planting, and measured lint yield from all site years.

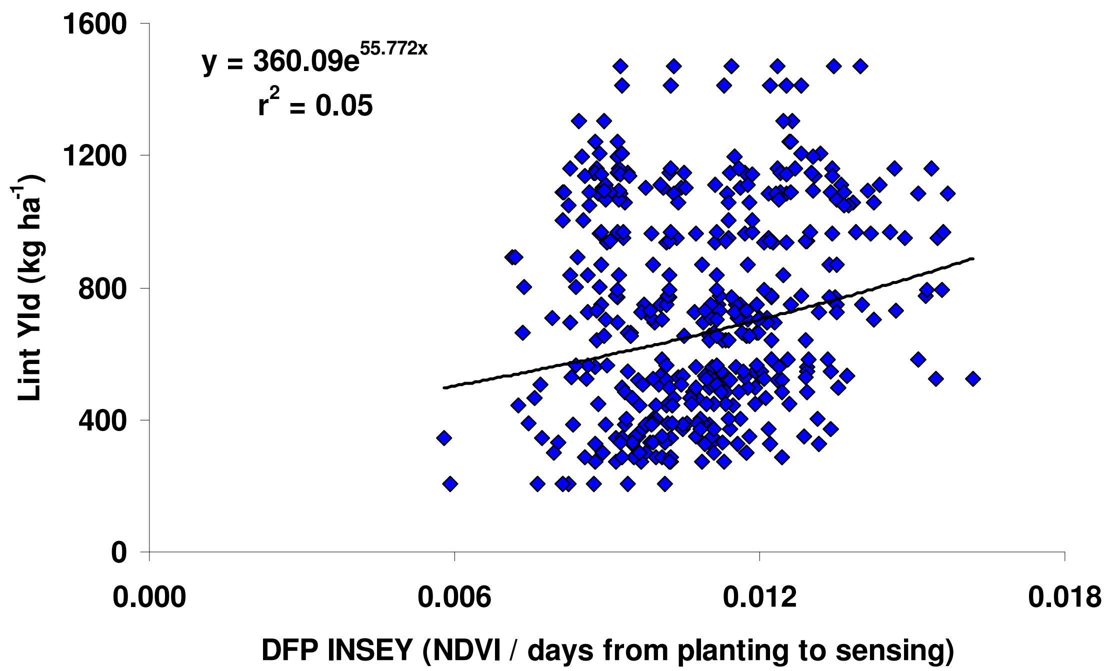

Figure 2. Relationship between in season estimate of yield (INSEY) computed from NDVI readings of cotton collected between 38 and 90 days after planting, divided by the number of days of planting to sensing, and measured lint yield from all site years.

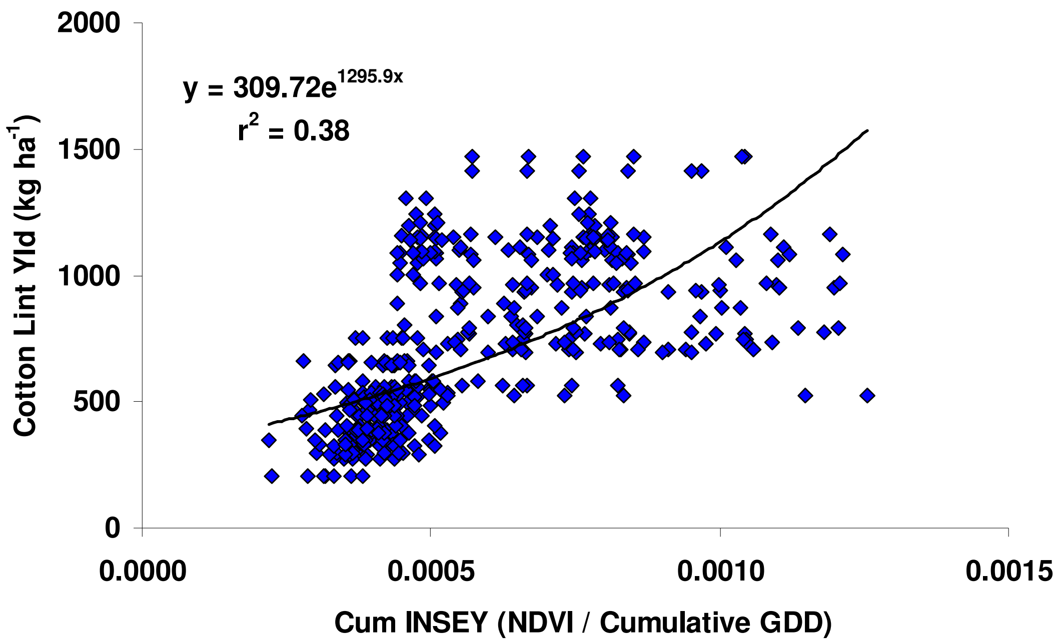

Figure 3. Relationship between in season estimate of yield (INSEY) computed from NDVI readings of cotton collected between 38 and 90 days after planting, divided by the number of days of planting to sensing, and measured lint yield from all site years.

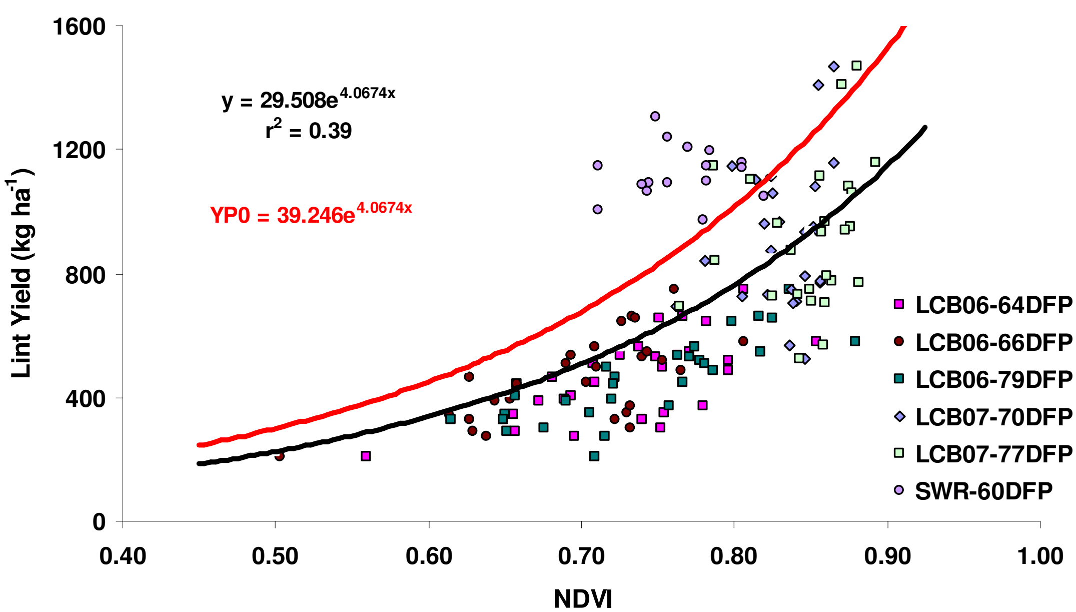

Figure 4. Relationship between the normalized difference vegetative index (NDVI) readings of cotton collected between 60 to 80 days after planting, and measured lint yield from all site years. Where YP0 = yield potential; YP0 calculated = the mean + one standard deviation.

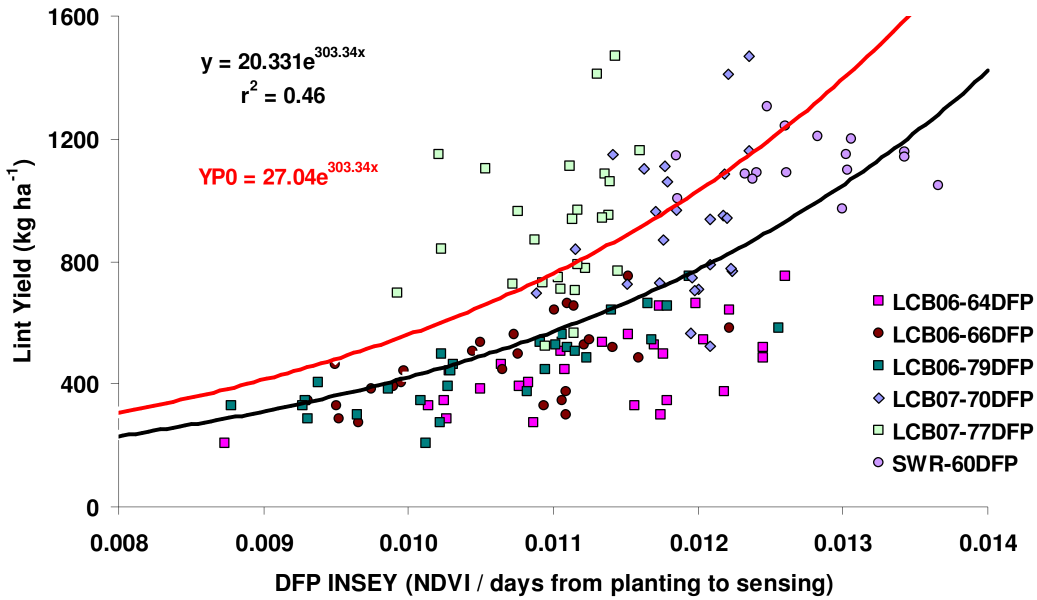

Figure 5. Relationship between in season estimate of yield (INSEY) computed from NDVI readings of cotton collected between 60-80 days after planting, divided by the number of days of planting to sensing, and measured lint yield from all site years. Where YP0 = yield potential; YP0 calculated = the mean + one standard deviation.

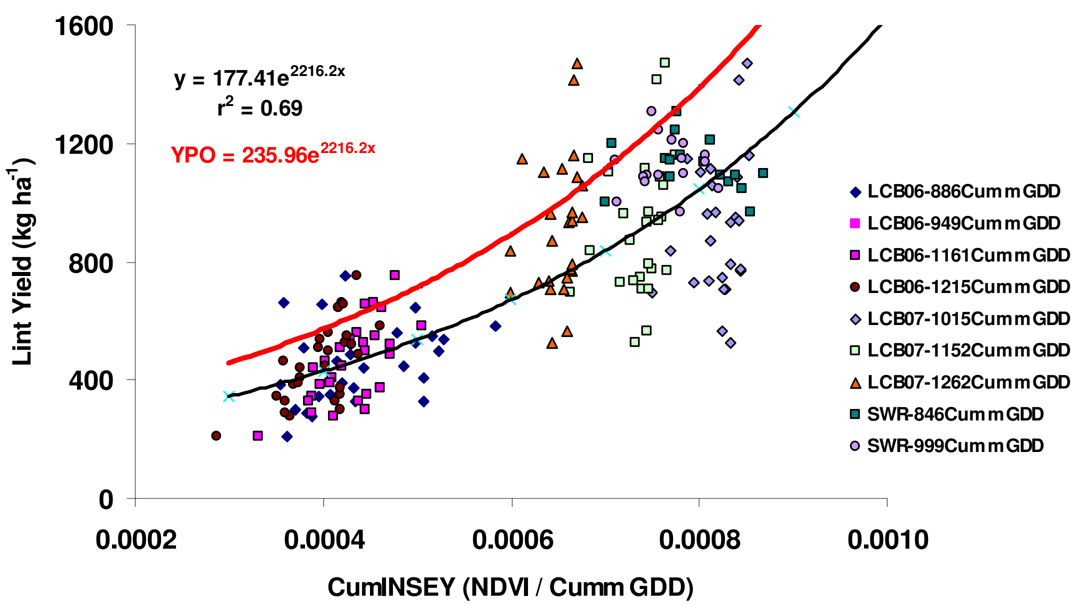

Figure 6. Relationship between in season estimate of yield (Cum INSEY) computed from NDVI readings of cotton at growth stages from square to peak bloom (800-1300 Cumm GDD), divided by the number of days of planting to sensing, and measured lint yield from all site years. Where YP0 = yield potential; YP0 calculated = the mean + one standard deviation.

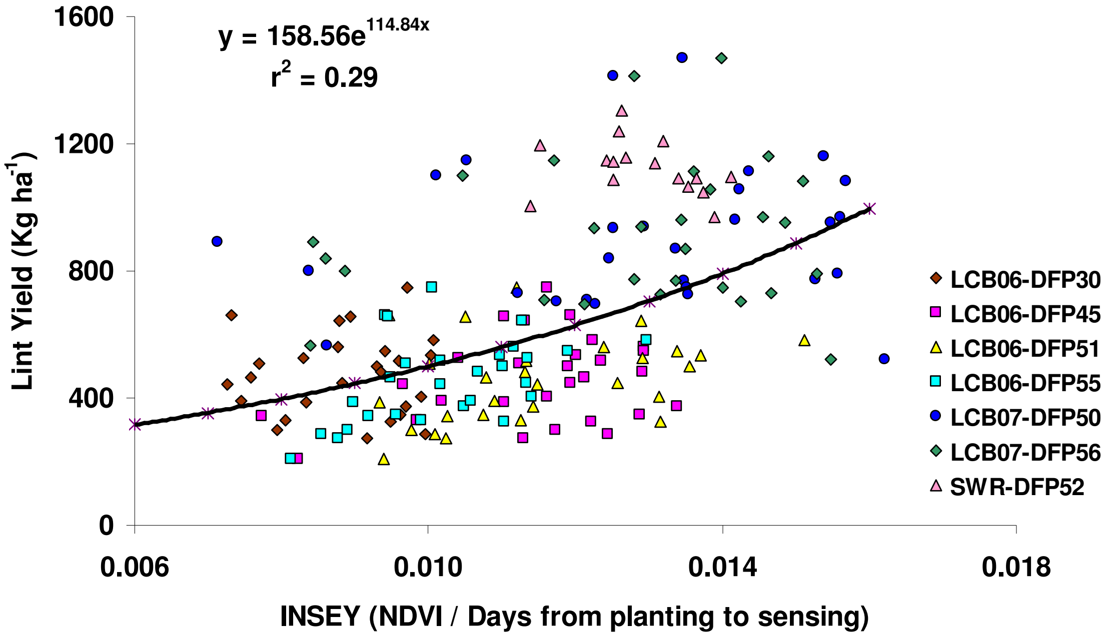

Figure 7. Relationship between in season estimate of yield (DFP INSEY) computed from NDVI readings of cotton collected between 30-56 days after planting, divided by the number of days of planting to sensing, and measured lint yield from all site years.

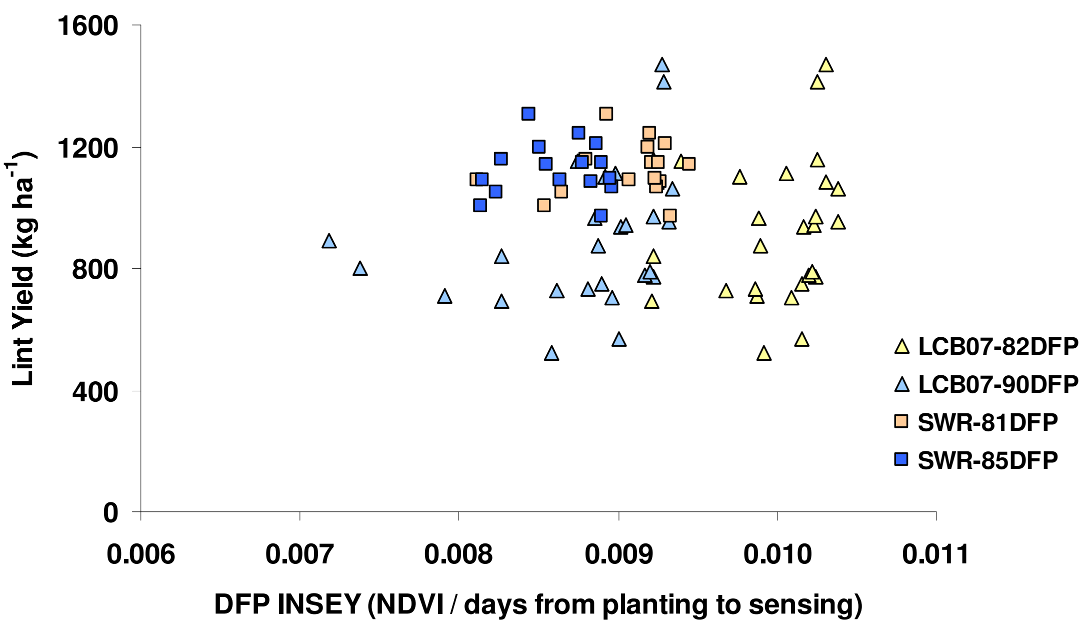

Figure 8. Relationship between in season estimate of yield (DFP INSEY) computed from NDVI readings of cotton collected between 81-90 days after planting, divided by the number of days of planting to sensing, and measured lint yield from all site years.

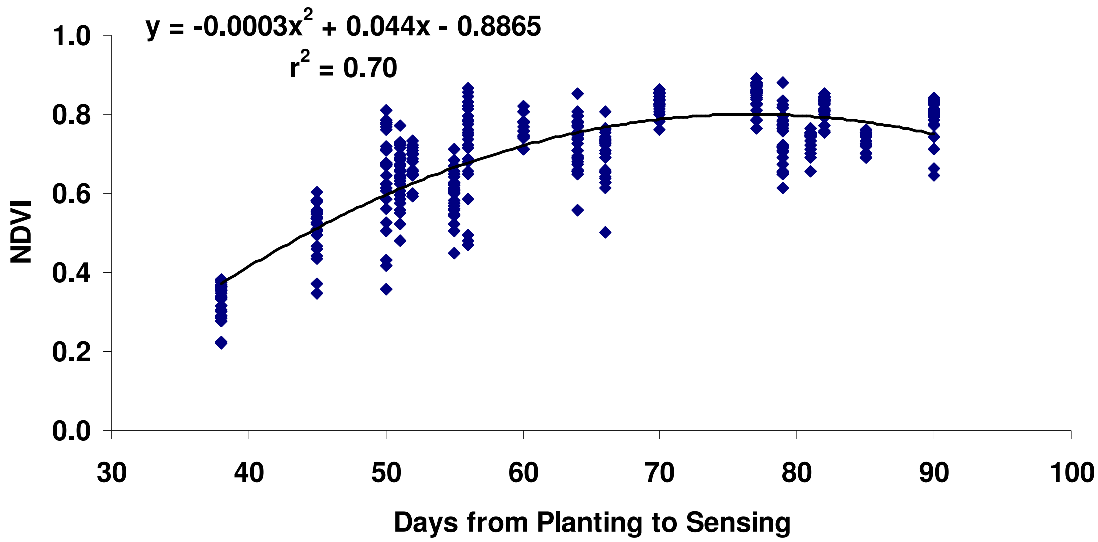

Figure 9. The trend of NDVI values as days from planting to sensing increases, from all sites all years.

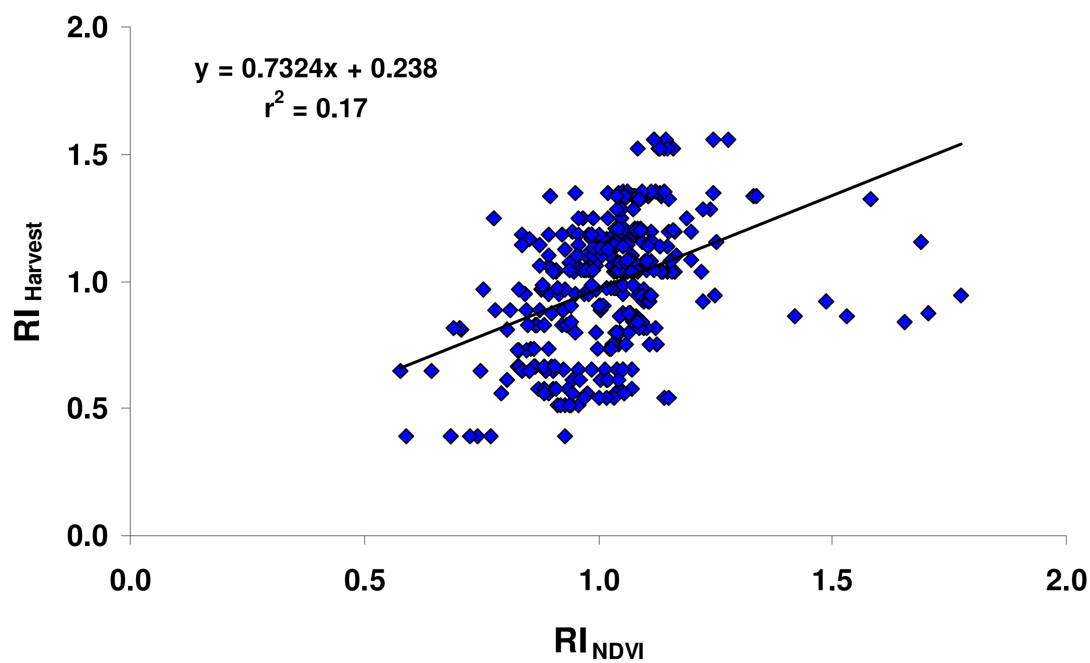

Figure 10. Relationship between the response index measured in season, (NDVI of fertilized plot / NDVI of check plot) from readings of cotton collected between 38 to 90 days after planting, and measured lint yield and the response index measured at harvest (yield of fertilized plot / yield of check plot) from all site years.

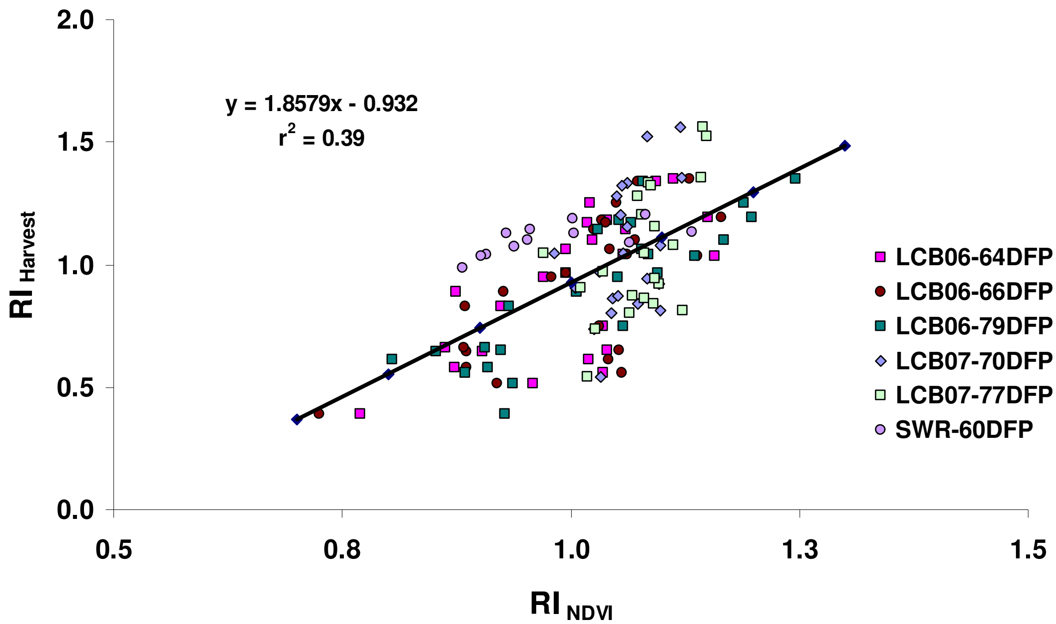

Figure 11. Relationship between the response index measured in season, (NDVI of fertilized plot / NDVI of check plot) from readings of cotton at growth stages from 60 to 80 days after planting, and measured lint yield and the response index measured at harvest (yield of fertilized plot / yield of check plot) from all site years.

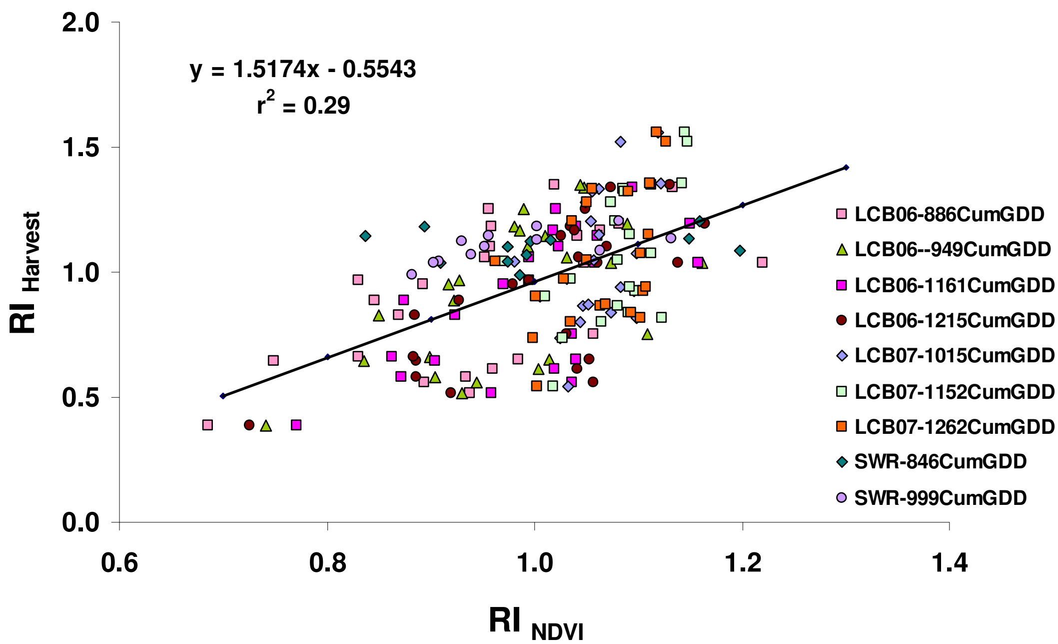

Figure 12. Relationship between the response index measured in season, (NDVI of fertilized plot / NDVI of check plot) from readings of cotton at growth stages from square to peak bloom (800-1300 Cumm GDD), and measured lint yield and the response index measured at harvest (yield of fertilized plot / yield of check plot) from all site years.

APPENDIX

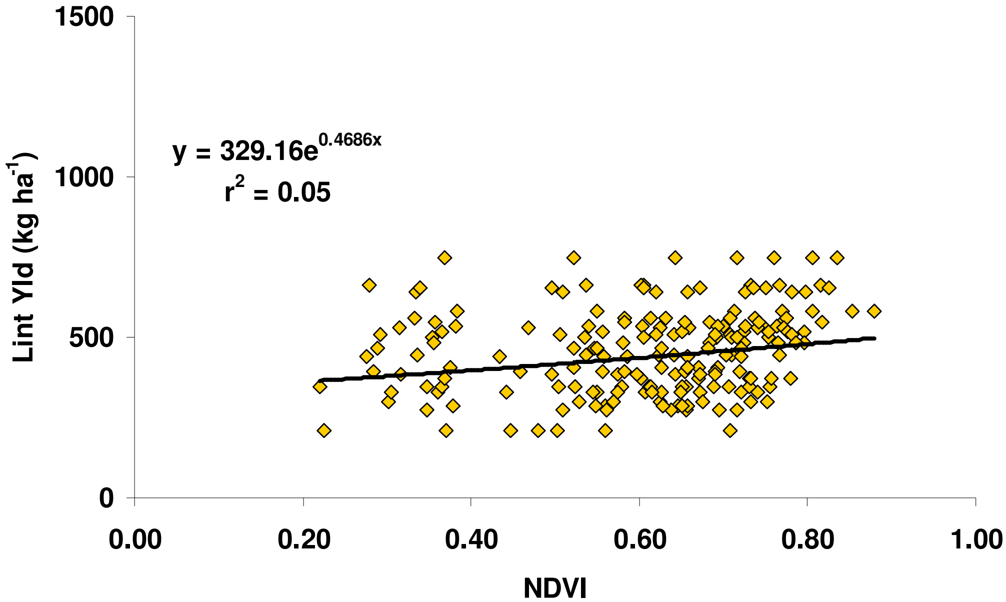

Figure A1. Relationship between the normalized difference vegetative index (NDVI) readings of cotton collected at growth stages of vegetative to mature boll (38 to 79 days after planting) and measured lint yield from Lake Carl Blackwell in 2006.

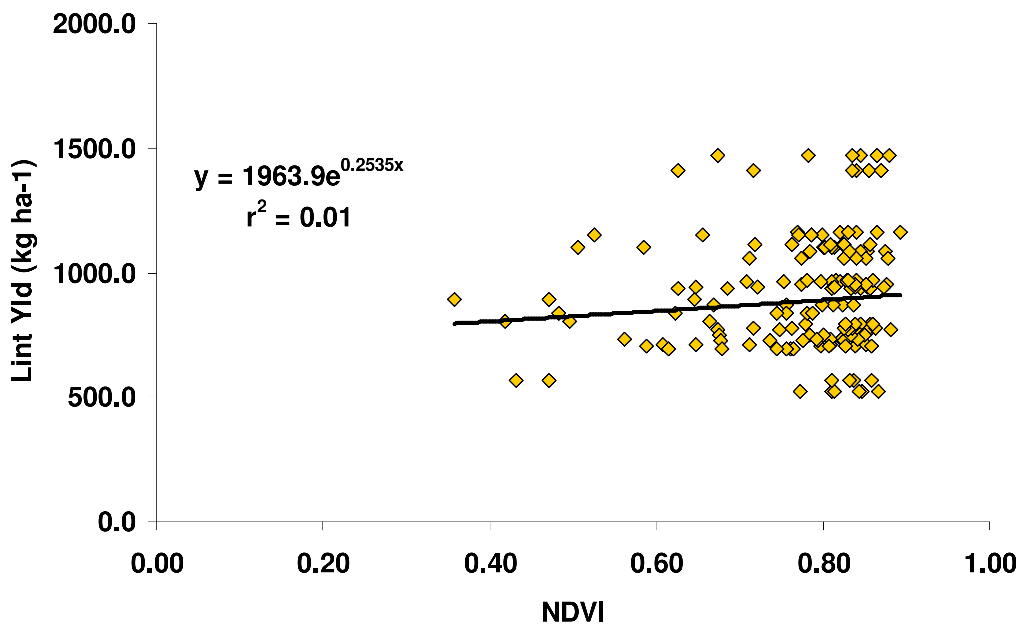

Figure A2. Relationship between the normalized difference vegetative index (NDVI) readings of cotton collected at growth stages of vegetative to mature boll (50 to 90 days after planting) and measured lint yield from Lake Carl Blackwell in 2007.

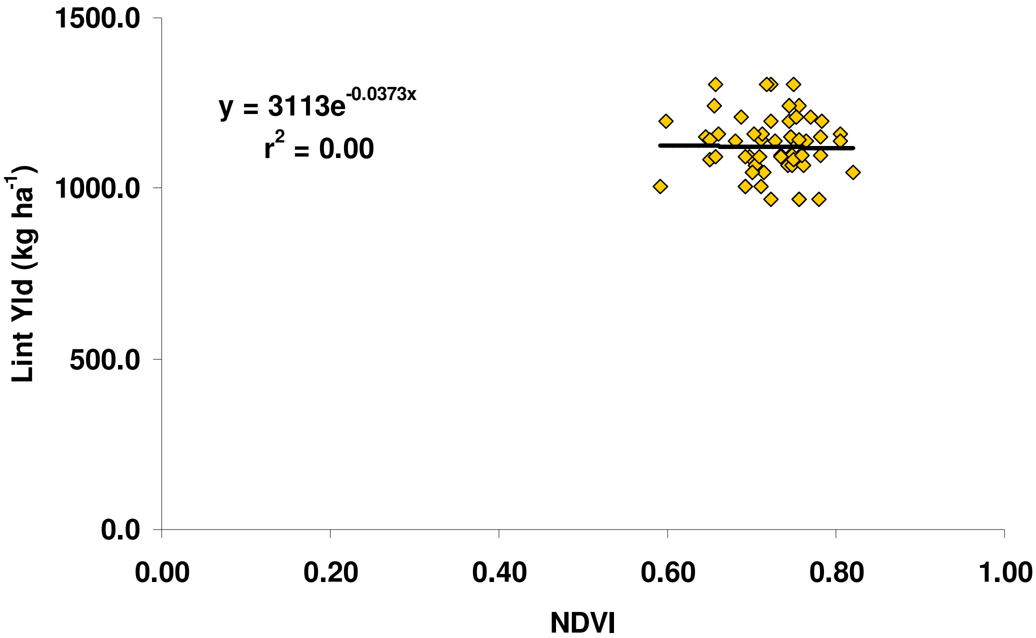

Figure A3. Relationship between the normalized difference vegetative index (NDVI) readings of cotton collected at growth stages of vegetative to mature boll (52 to 85 days after planting) and measured lint yield from South West Research Station in 2007.

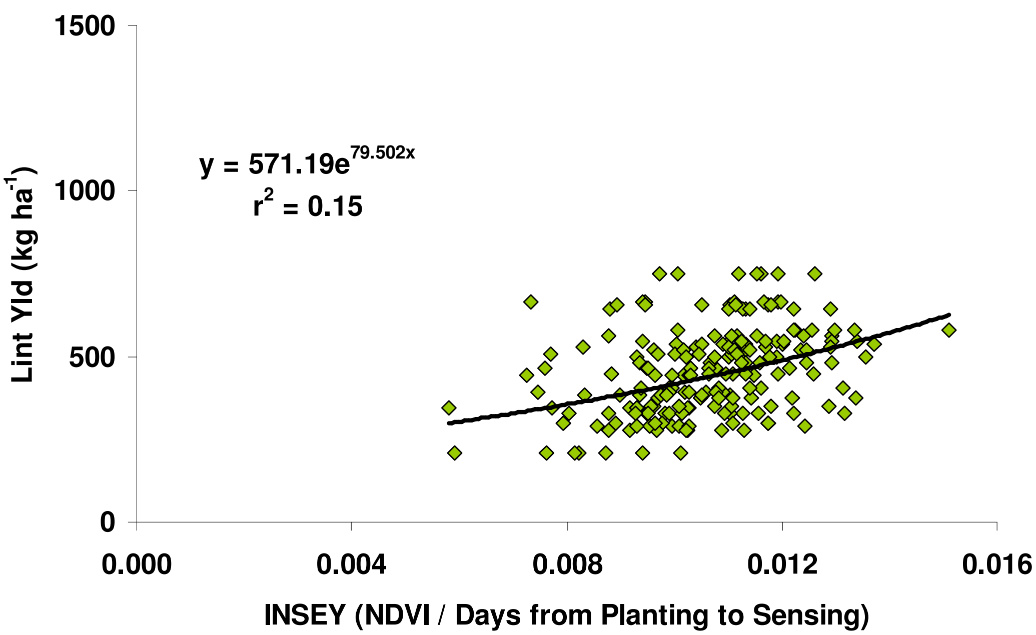

Figure A4. Relationship between in season estimate of yield (INSEY) computed from NDVI readings of cotton collected at growth stages sensed (38 to 79 days after planting), divided by the number of days of planting to sensing, and measured lint yield from Lake Carl Blackwell in 2006.

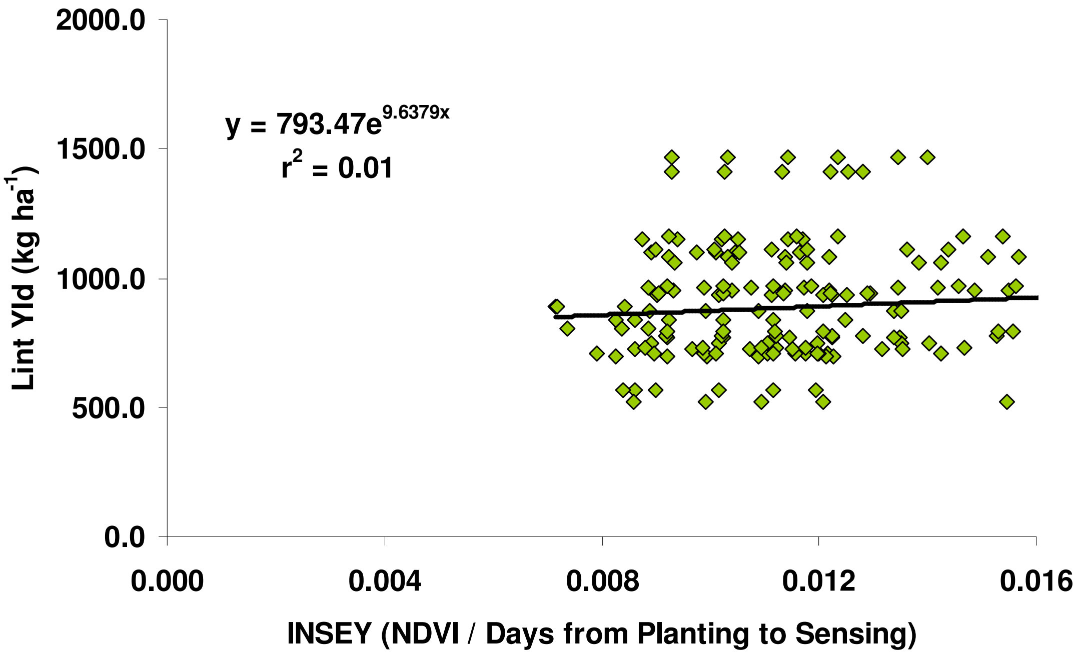

Figure A5. Relationship between in season estimate of yield (INSEY) computed from NDVI readings of cotton collected at growth stages sensed (50 to 90 days after planting), divided by the number of days of planting to sensing, and measured lint yield from Lake Carl Blackwell in 2007.

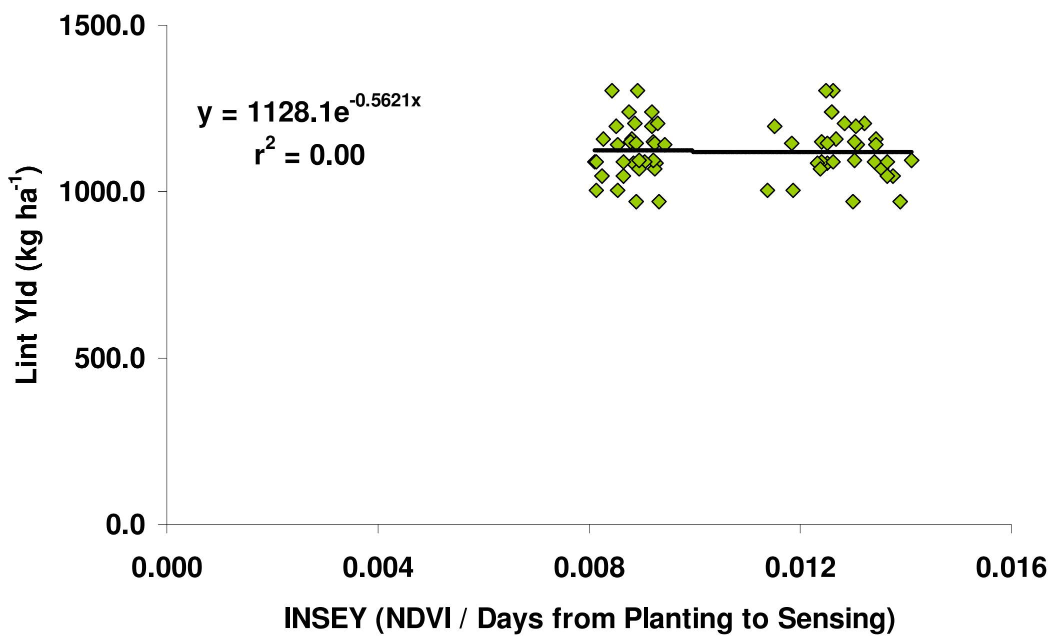

Figure A6. Relationship between in season estimate of yield (INSEY) computed from NDVI readings of cotton collected at growth stages sensed (52 to 85 days after planting), divided by the number of days of planting to sensing, and measured lint yield from South West Research Station in 2007.

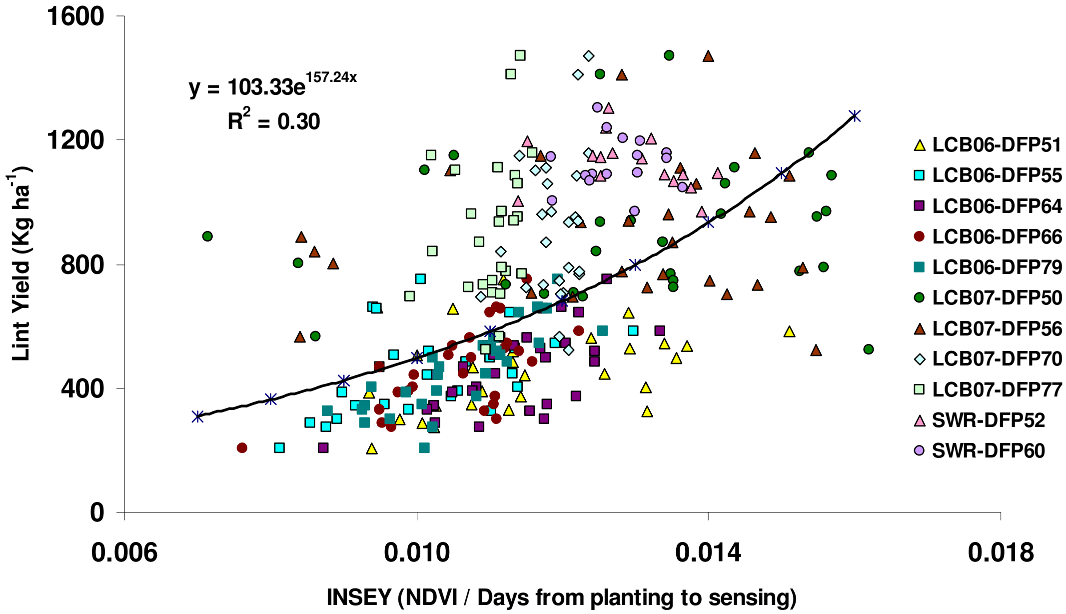

Figure A7. Relationship between in season estimate of yield (INSEY) computed from NDVI readings of cotton collected between 50-80 days after planting, divided by the number of days of planting to sensing, and measured lint yield from all site years.

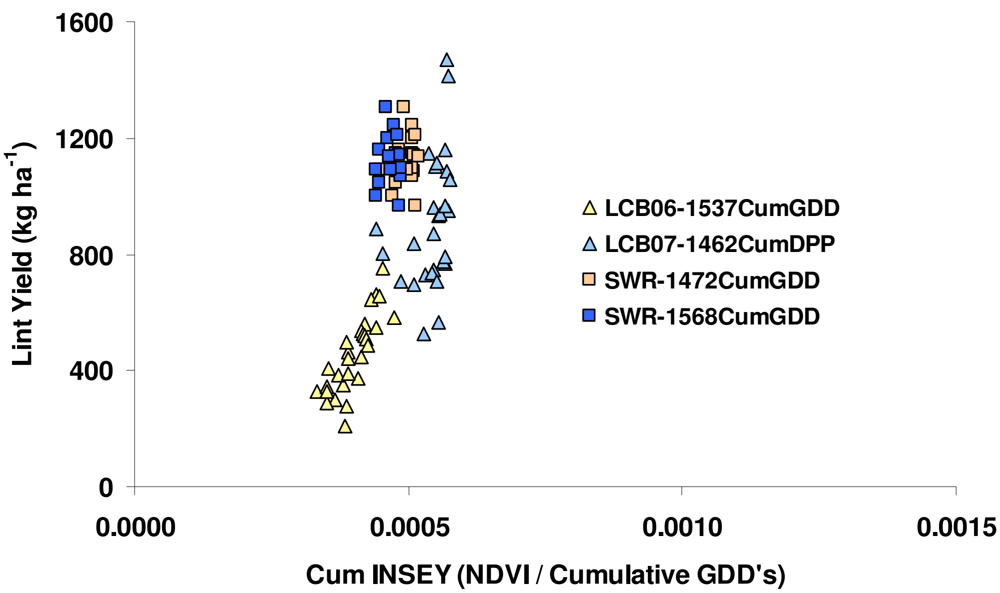

Figure A8. Relationship between in season estimate of yield (Cum INSEY) computed from NDVI readings of cotton at growth stages from square to peak bloom (800-1300 Cumm GDD), divided by the number of days of planting to sensing, and measured lint yield from all site years.

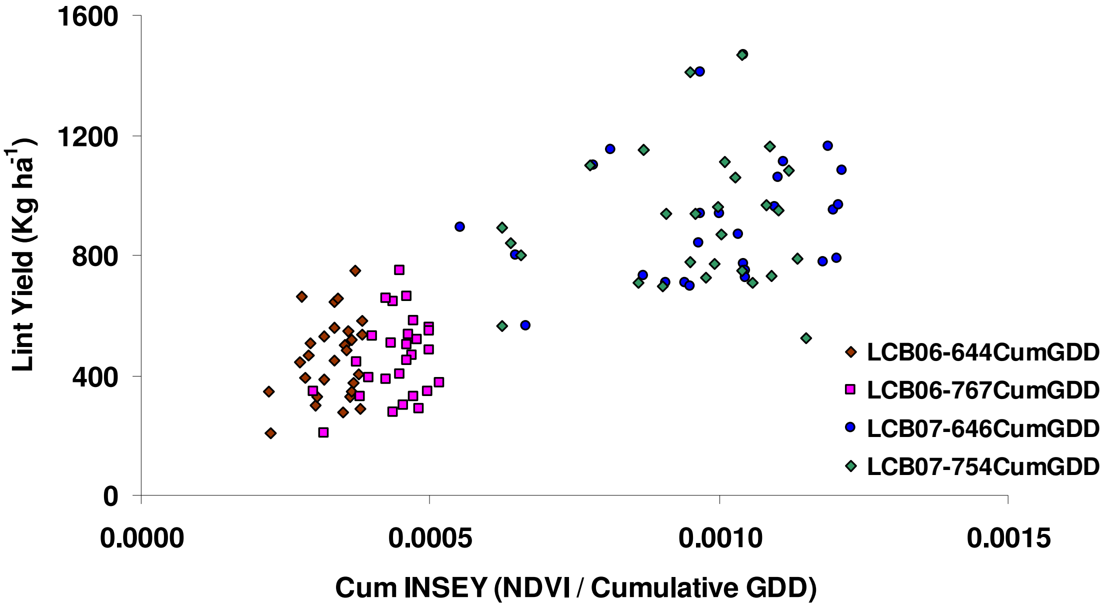

Figure A9. Relationship between in season estimate of yield (Cum INSEY) computed from NDVI readings of cotton at growth stages from vegetative to pin-head square (0-800 Cumm GDD), divided by the number of days of planting to sensing, and measured lint yield from all site years.

VITA

Daryl Brian Arnall

Candidate for the Degree of

Doctor of Philosophy

Dissertation: ANALYSIS OF THE COEFFICIENT OF VARIATION OF REMOTE SENSOR READINGS IN WINTER WHEAT, AND DEVELOPMENT OF A SENSOR BASED MID-SEASON N RECOMMENDATION FOR COTTON.

Major Field: Soil Science

Biographical:

Personal Data: Born in Miami, Oklahoma, on June 27, 1980.

Education: Graduated from Wyandotte High School, Wyandotte, Oklahoma in May 1998; received Associate of Art degree from Northeast Oklahoma A&M College, Miami, Oklahoma in May 2000; received Bachelors of Science degree in Plant and Soil Science from Oklahoma State University, Stillwater, Oklahoma in December, 2002. Completed the requirements for Master of Science degree with a major in Plant and Soil Sciences at Oklahoma State University in December 2004. Completed the requirements for the Doctor of Philosophy degree with a major in Soil Science at Oklahoma State University in May 2008.

Experience: Employed by Oklahoma State University, Soil Water Forage Analytical Laboratory, 2000-2002,; employed by Oklahoma State University, Department of Plant and Soil Sciences as a graduate research assistant, 2002-2006; employed by Oklahoma State University, Department of Plant and Soil Sciences as a senior agriculturist, 2006-present.

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Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: ANALYSIS OF THE COEFFICIENT OF VARIATION OF REMOTE SENSOR READINGS IN WINTER WHEAT, AND DEVELOPMENT OF A SENSOR BASED MID-SEASON N RECOMMENDATION FOR COTTON.

Pages in Study: 90 Candidate for the Degree of Doctor of Philosophy

Major Field: Soil Science

Scope and Method of Study: For chapter one, Hard red winter wheat (Triticum aestivum L.) experiments were conducted to better understand how the coefficient of variation (CV) could be used to better mid-season N rate recommendations. The CV's were calculated from the normalized difference vegetation index (NDVI) collected from each plot with a GreenSeeker™ Hand Held optical reflectance sensor. For chapter two, Cotton (Gossypium *hirsutum* L.) experiments were conducted to evaluate if spectral reflectance measurements could predict yield mid-season and be used to determine a mid-season N rate recommendation.

Findings and Conclusions: For chapter one, CV was found to be a good predictor of plant population and when used as a component of mid-season response index calculation improved the relationship with the response index measured at harvest in terms of yield. A relationship between yield and CV was also observed. This work indicated that a previously proposed $RI_{NDVI\text{-}CV}$ equation did not improve the prediction of the RI at harvest. For chapter two, over sites and years lint yield was predicted using the division of NDVI and Cumulative Growing Degree Day (CummGDD) units that accumulated from planting to sensing, the prediction was best when data was collected between 800 and 1300 CummGDD. The yield prediction model combined with the establishment of the relationship between the response index at harvest and mid-season; a nitrogen fertilization optimization algorithm was developed.

ADVISER'S APPROVAL: Dr. William Raun