# RELATIONSHIP BETWEEN THE RESPONSE INDEX DETERMINED IN-SEASON AND AT HARVEST AND THEIR USE FOR DETERMINING TOPDRESS NITROGEN RATES IN WINTER WHEAT

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# ABSTRACT

Current methods for making nitrogen recommendation for winter wheat (*Triticum aestivum* L.) do not adjust for in-season temporal variability of plant available non-fertilizer nitrogen (N) sources. The purpose of this study was to compare the use of different nitrogen response indices determined in-season ($RI_{NDVI}$ and $RI_{PLANTHEIGHT}$) to the nitrogen response index measured at harvest ($RI_{HARVEST}$). In addition this study evaluated the use of the in-season response indices for determining topdress nitrogen rates for winter wheat. Nine experiments were conducted over two years and eight locations. A randomized complete block design with nine different treatments with four replications was used at each location. Preplant nitrogen source was ammonia nitrate (34-0-0). At Feekes 4-6, $RI_{NDVI}$ was measured for use in determination of topdress nitrogen rates. The nitrogen source for topdressing was UAN (28-0-0). Both $RI_{NDVI}$ and $RI_{PLANTHEIGHT}$ were able to predict $RI_{HARVEST}$ ($r^2 = 0.75$ and $r^2 = 0.74$, respectively). Because the sensor based approach for making N recommendations relies on information obtained from the sensors, $RI_{NDVI}$ should be used to estimate a site's potential for response to additional nitrogen. Yet, if a handheld sensor is not available or affordable, then $RI_{PLANTHEIGHT}$ will predict $RI_{HARVEST}$ reliably for managing nitrogen inputs for temporal variability. The use of sensor based nitrogen recommendations were just as profitable compared to traditional nitrogen management schemes employed today by winter wheat producers. Further findings indicate that the estimated nitrogen use efficiency for topdress N applications is likely less than 70 percent, and more realistically near 50 percent.

# INTRODUCTION

Common fertility management implemented by producers is to take a composite soil sample of an area, usually from 2.5 to 160 acres, evaluate nitrate nitrogen in the soil system through a soil test, subtract this amount from that needed to reach a certain yield goal, and fertilize that area based on this information. This research aims to look at a new tool that can be used in managing nitrogen inputs for hard red winter wheat cropping systems.

After reviewing yield data from a long-term soil fertility research trial in dry land winter wheat, Johnson and Raun (2003) proposed a response index, which measures the plant response to nitrogen fertilizer in terms of grain yield in a particular growing season. A response index was calculated by taking the highest yielding fertilized grain plot and dividing by the control yield (0 N applied).

Oklahoma State University's soil fertility group has set a goal for trying to increase nitrogen use efficiency from its current level of only 33 percent world wide for cereal grain production (Raun and Johnson, 1999). Being able to predict the magnitude of response that winter wheat will have to additional topdress fertilizer during the growing season would provide one way of reaching this goal. Furthermore, given the low prices for hard red winter wheat and associated high prices of N fertilizer (due to shortages of natural gas, a key component used to manufacture N fertilizer), wheat producers are looking for methods to cut fertilizer costs and maintain yield levels. A one percent increase in nitrogen use efficiency (NUE) would save around $234,658,462 worldwide while a 20 percent increase would have savings in excess of $4.7 billion per year (Raun and Johnson, 1999).

In 1999 the United States used more than 11,165,310 Mg of nitrogen fertilizer (FAO 2001). It is believed that a large portion of environmental pollution from N sources comes from their use in agriculture cropping systems. The pollution results when producers apply excess N to insure against a change in growing conditions where the crop might benefit from the extra N that might otherwise result in reduced yield. Goolsby et. al. (2001) reported that the mean annual discharged flux of all forms of N in the Mississippi and Atchafalaya River Basin was 1,568,000 Mt $yr^{-1}$ for the time period between 1980 to 1996. Jaynes et. al. (2001) reported in a study of N in tile drainage that even at the lowest N treatment rate (67 kg N $ha^{-1}$), $NO_3$-N levels exceeded the maximum contaminant limit of 10 mg $NO_3$-N $L^{-1}$ set by the USEPA for drinking water. With these pollution problems, methods for applying N to a cropping system that will increase efficiency and maintain or increase yield while lowering the amount of nitrogen contamination in fresh water supplies must be developed by researchers and employed by agriculture producers.

## LITERATURE REVIEW

Agronomic crops have been intensively studied to find the optimum N fertilizer rate to produce crops most efficiently. Homenauth et al. (1986) reported that the economically optimum N rate for sunflowers in Mississippi is between 76 and 116 kg N $Ha^{-1}$. Pearson and Jacobs (1987) found N supplied before anthesis increases maize grain yield more than N supplied after anthesis. Rhoads and Manning (1986) stated that maize has a 90% chance of achieving a yield increase when N applications are initiated at emergence. They further noted that by waiting one week after seedling emergence to start applications of N resulted in increased N uptake in the plant when it was measured forty-one days after planting.

Eckert et. al. (1986), found that when testing the effects of crop residue on N fertilizer response to no-till corn, check yields were higher for corn grown in soybean stubble from the previous year, than corn grown in the stubble of the previous year's corn crop. They also noted differences in grain yield due to the type of N source used in no-till corn after corn. Urea-ammonium nitrate solution (UAN) and urea produced the lowest grain yields throughout the two-year study compared to anhydrous ammonia. The differences were associated with corn residue having a higher C: N ratio that immobilized the surface applied fertilizer that was not already lost by volatilization. Rasmussen and Rohde (1991) noted similar results in a winter wheat trial comparing stubble mulch operations to clean till operations to evaluate the effects on NUE. They reported that grain yield is more sensitive to growing season precipitation than tillage operation, thus explaining the combined direct relationship found between N rate and precipitation.

Many scientists have made an effort to predict N mineralization rates throughout the growing season as an indirect indication of potential N response. One such method is a pre-side-dress soil nitrate test (PSNT) (Magdoff et. al , 1984). Evanylo and Alley (1997) reported that only five out of seventeen corn sites in 1990 and eight out of thirty sites in 1991 responded significantly to a sidedress application of N fertilizer in Virginia. They attributed this insignificant N fertilizer response to amendments made to the soil with organic N sources and not high soil test inorganic N. They also noted that the environment prior to soil sampling may have provided poor conditions for the N mineralization process (large leaching rain, cool soils and/or extremely dry or wet soils) and conditions could have improved after the samples were taken.

Another way to estimate N mineralization is to use a model. Greenwood et. al. (1987), developed a model by which estimated the response to N fertilizer of diverse crops. They indicated that the amount of N mineralized is proportional to soil temperature at depth of 10 cm, and declines exponentially with depth past 10 cm. This mineralization model utilized several variables: volumetric water content at field capacity, initial distribution of mineral N down the soil profile and corresponding soil moisture deficit, monthly evapotranspiration, and soil temperature among others. They concluded that the number of quite different variables in the model had a substantial effect on N requirements. They suggest that the fertilizer N requirement will seldom be well correlated with any one of the variables. However, this model has one major potential flaw; it does not account for the variability of soil types within a field. Another N mineralization model was developed by Hadas et. al. (1989) to predict mineralization at various depths in the soil. They observed considerable amounts of N mineralized under field conditions in the soil layers below 20 cm. Further, while developed in a laboratory, their model over-estimated field mineralization by only 13 to 26 percent.

Johnson and Raun (2003) suggested that N mineralization over a season could be estimated by the use of a response index. They found that the grain yield response to N fertilizer was more variable than the grain yields of the control (0 N) and the maximum fertilized grain-yielding treatment in a long-term winter wheat study at Lahoma, Oklahoma. They verified this trend by finding similar results in a long-term Nebraska irrigated corn (*Zea mays* L.) study.

Methods of visually observing plant conditions are often the only diagnostics used to determine nutrient deficiencies in season. Johnson and Raun (2003) developed a method to assist winter wheat producers in determining in-season response to additional N fertilizer. This method involved installing a strip of N fertilizer that is twice the rate (or non-N-limiting) used during pre-plant fertilization. Implementing this zone allows the producer to visually quantify the likelihood of achieving an in-season response to N fertilizer. If the non-N-limiting strip is not visible to the producer, then this would be indicative that minimal or no N response is likely, since adequate N was already available from preplant fertilization, N mineralization, and/or rainfall.

One problem in addressing variability in fields has been the resolution at which to properly manage spatial differences. Kachanoski and Fairchild (1996) used statistical equations to describe the average grain yield on a field basis from the application of a single constant rate of fertilizer, in fields with variable soil. They suggested that the relationship between yield response, soil test and applied fertilizer are non-linear, and a single calibration (recommended fertilizer versus soil test) cannot exist for fields with different degrees of spatial variability. They further stated that calibrations obtained from sites with low soil test variability would not hold for sites with higher variability. Furthermore, they said that calibrations obtained from sites with low soil test variability would under predict the optimum fertilizer rate for maximum economic yield for sites with high variability.

Solie et. al. (1999) looked at what field size element researchers and producers should be using to address the variability of soil in a particular field to make fertilizer N recommendations. To do this they performed rigorous soil sampling on two, 2 X 20 m areas in established Bermudagrass that appeared to be visually homogeneous. These selected areas were broken into 490, 0.3 m by 0.3 m subplots. Eight soil cores (0-15 cm) were taken from each 0.3 m by 0.3 m and mixed together and analysis was completed on five soil variables (total N, extractable P and K, organic C, and pH) and two plant variables (forage-total N and biomass). Semivariance analysis was performed on the data and the authors found that the optimum field element size for N fertilization was 1.0 X 1.0 m or smaller. These results were similar to those discovered by LaRuffa et. al. (2001) when looking at the optimum field element size for maximum yields in winter wheat, using variable nitrogen rates. They found that there was a trend for finer resolutions (< 54 $m^2$) to have increased nitrogen use efficiency in high yielding winter wheat environments.

Estimating crop yield has been the most common effective way to apply nitrogen, and other soil mobile nutrients. If the final yield is known or accurately estimated, then the nutrient can be applied based on the respective plant need to achieve that yield. Lamb et. al. (1997) looked at the effects of spatial and temporal variability on the stability of corn grain yields and the use of yield maps to make recommendations. They recorded four years of data and tried to predict the fifth year's yield for each cellblock of the field. They reported that when the four years of data were averaged and then correlated with the fifth year, the r-value was 0.68. When they dropped the data from the best and worst years, the r values decreased to 0.60 and 0.57 respectively. They determined that yield is unstable and that using yield maps to make future predictions about yield is not precise enough for making management decisions, even if yield from several years is used. Colvin et. al. (1997) found similar results from their study in central Iowa, which used ten years of yield data.

With the further development of optical sensing technology, many researchers have been investigating the possibility of predicting crop yield by light absorbance (Coldwell, 1956; Jordan, 1969; Tucker, 1979; Seller, 1985, 1987 Stone et. al. 1996 a, b; Shanahan et. al. 2001). Ma et. al. (1996) reported that canopy light reflectance values at 600 nm (Red light) and 800 nm (NIR light), could be used to calculate the Normalized Difference Vegetative Index (NDVI). NDVI is defined as ((NIR - RED) / (NIR + RED)) and was found to be strongly correlated with grain yield. This correlation increased up to anthesis. They also stated that NDVI was better at differentiating N treatment effects than any other wave bands and that NDVI was correlated with leaf area and leaf chlorophyll as well.

Lukina, et. al. (2001) published an N fertilization optimization algorithm (NFOA) for winter wheat based on in-season estimates of yield and plant N uptake. The optical sensor that was used in this work measured both incident and reflected light to calculate NDVI values based on reflectance. By using reflectance NDVI, early-season plant N uptake was reliably predicted ($R^2$= 0.75) at growth stages between Feekes 4 to 6. It was also noted that average N uptake, over nine experiments between Feekes growth stage 4 to 6, was 45 kg N $ha^{-1}$ . This represented over half of the total nitrogen that was removed by the grain at harvest. Lukina et. al.(2001) indicated that NDVI measured at the same time, was positively correlated with final grain yield. By dividing NDVI by the number of days from planting to date of sensing, ensuing work found a more reliable method of estimating yield than the earlier method by using cumulative growing degree days (days where growing degree days $(((T_{min} + T_{max})/2)-4.4^0C)$ were greater than zero (Raun et al 2001)) as the divisor. Lunkina et. al. (2001) outlined a procedure to determine the N fertilizer rate to be applied in a topdress application based on the yield potential of that crop, and is as follows.

1. Predict potential grain yield (PGY) form the grain yield-INSEY equation PGY in (Mg $ha^{-1}$) = $0.74076+0.19219\ e^{577.63INSEY}$.
2. Predict percent N in the grain based on predicted grain yield. Percent N in the grain = $0.0704PGY^2 – 0.5298PGY + 3.16$.

3. Calculate predicted grain N uptake (predicted percent nitrogen in the grain multiplied by predicted grain yield).
4. Calculated predicted early-season plant nitrogen uptake for NDVI. Early season plant nitrogen uptake (kg ha$^{-1}$) = $14.76+0.7758\ e^{5.468NDVI}$.
5. Determine in-season topdress fertilizer nitrogen requirement = (predicted grain nitrogen uptake-predicted early-season plant N uptake)/0.70.

Mullen et. al. (2003) reported that computing an in-season response index (RI) from N induced NDVI differences ($RI_{NDVI}$) at Feekes 5 (Large 1954) over 4 years taken from 22 locations was well-correlated ($r^2 = 0.56$) with RI measured at harvest ($RI_{HARVEST}$). The $RI_{NDVI}$ was determined by dividing plots that were non-N-limiting, by a zero N check plot. Raun et. al. (2002) incorporated $RI_{NDVI}$ into the NFOA outlined by Lukina et. al. (2001). Raun et al. (2002) applied fertilizer based on the difference in grain N uptake for $YP_N$ (estimated yield potential if N fertilizer is added, $YP_N = PGY \times RI_{NDVI}$) and N uptake in the forage at Feekes 4-6. Using this method they reported an average increases in NUE of 15 percent compared to treatments that used similar or more N, applied either preplant and/or topdress. Thus, to use this practice, a producer will still have to install a non-N-limiting area.

A method for finding a reliable, in-season estimate of the crop's response to additional topdress N that does not rely on an induced N non-limiting area would be desirable. As this method could reliably predict the final response with out incurring additional costs of installing a non-N-limiting strip or area, thus improving overall profitability. Work done on the field element size (Solie et. al. 1999), and the micro-variability of mobile and immobile soil nutrients (Raun et. al., 1998) illustrates the highly variable nature of soil nutrients. Knowing the optical sensor field element size (Solie et. al. 1996) for measuring plant N uptake using light reflectance is <1.5 $m^2$, it may be possible to develop a reliable in-season estimate of RI based on spatial variability ($RI_{SV}$) of plant available soil N. $RI_{SV}$ is defined by the equation: (Mean NDVI + 1 standard error) / (Mean NDVI – 1 standard error). The mean and the standard error for NDVI is calculated from all randomly selected field element sizes measured. $RI_{SV}$ can be determined from sensor readings collected anywhere within fields not having the non-N-limiting (N-rich) strip.

Furthermore, a method for producers to reliably measure a site's potential response to additional N, without using a sensor to measure $RI_{NDVI}$, needs further evaluation. This non-sensor based in-season RI would be of benefit to farmers in developing countries or a farmer in a developed country that can not afford a sensor or skeptical of its use in a N management scheme. A potential non-sensor based in-season response index could be based on differences in any crop characteristic that responds to N. Crop canopy height ($RI_{PLANTHEIGHT}$) is responsive to N availability and should be a good measure, right before making a topdress N application, which is the same time one would measure $RI_{NDVI}$ with a sensor. $RI_{PLANTHEIGHT}$ would be measured the same way as $RI_{NDVI}$, (Mean plant height of N-rich) / (Mean plant height of check).

# OBJECTIVES

The objectives of this experiment were to: 1) determine the relationship between in-season spectral reflectance measured RI and RI measured at harvest; 2) determine the relationship between crop canopy height at the time of application of top-dress N fertilization and RI based on spectral reflectance; and 3) evaluate the nitrogen fertilization optimization algorithm developed at Oklahoma State University.

# MATERIALS AND METHODS

In the fall of 2001 five short-term winter wheat experiments were established, three of these trials were placed in selected wheat farmer fields in Kingfisher County, Oklahoma and two at the Stillwater Experiment Station in Stillwater, Oklahoma. In the fall of 2002 three different sites were used in addition to the one at the Efaw upland site. The soils for these eight selected sites are reported in Table 1, along with preplant soil test data. Plot management dates, varieties and harvest information for all sites and years are reported in Tables 2 and 3.

A randomized complete block design was used with nine different N management treatments replicated four times at each site. The treatment structure is provided in Table 4. Plot sizes are 1.52 m by 1.52 m. The NDVI was measured between Feekes growth stages 4 to 6 (Large 1954), on all plots both years.

Treatment one is the check with zero N applied either preplant or topdress. For all NFOA treatments that estimated grain N uptake used for topdress N calculation, 2.39 percent N in grain was used. Thus, grain N uptake equals estimated yield potential (YP) times percent N in grain (YP x 0.0239). Treatment two (forage NFOA), is a topdress N application for which the rate is calculated utilizing the NFOA outlined by Raun et. al. (2002). The N recommendation for this algorithm is determined from the estimated amount of grain N uptake at $YP_N$ (estimated yield potential if additional N is applied, $YP_N = YP_0 \times RI_{NDVI}$, $YP_0$ = estimated grain yield if zero N is added) minus the estimated amount of N taken up by the forage.

Treatment three (grain NFOA), is a topdress N application in which the N rate is calculated from the estimated amount of grain N uptake at $YP_N$ subtracted from the estimated amount of grain N uptake at. Treatment four (2x grain NFOA) used the same algorithm as treatment three except that $RI_{NDVI}$ is multiplied by two, this inflated $YP_N$ to twice the amount estimated for treatment 3. Fertilizer N recommendation is then the estimated amount of grain N uptake at the inflated $YP_N$ minus the estimated amount of grain N uptake at $YP_0$. A nitrogen use efficiency 70 percent was assumed for all NFOA N recommendation (Dahnke and Johnson, 1990; Hauck, 1973). Therefore, all NFOA N recommendation rates were divided by 0.7. However, with respect to treatment four (2 x Grain NFOA), the same N recommendation for this treatment can be derived from using 0.35 as the divisor for nitrogen use efficiency factor instead of 0.7 for treatment three (0.7 / 0.35 = 2.0).

Treatments five thru eight represent traditional N management schemes used by winter wheat farmers in this region. Treatment five is the application of 45 kg N $ha^{-1}$ topdress only. Treatment six is applying 45 kg N $ha^{-1}$ preplant with 45 kg N $ha^{-1}$ topdress. Treatment seven is an application of 45 kg N $ha^{-1}$ preplant only. Treatment eight is an application of 90 kg N $ha^{-1}$ preplant only. Treatment nine is the application of 45 kg N $ha^{-1}$ preplant and topdressing with the grain NFOA.

NDVI was measured using a GreenSeeker ™ hand held optical sensor unit. The handheld optical sensor unit measures NDVI using self-contained illumination in both the red (650 ± 10 nm full width half magnitude (FWHM)) and NIR (770 ± 10 nm FWHM) light bands. The device measures the fraction of the emitted light in the sensed areas that is returned to the sensor (reflectance). These fractions are used with the sensor to compute NDVI according to the following formula: $NDVI = (F_{NIR} - F_{RED}) / (F_{NIR} + F_{RED})$, where $F_{NIR}$ is the fraction of emitted NIR radiation returned from the sensed area, and $F_{RED}$ is the fraction of emitted Red radiation returned from the sensed area. The area sensed by this handheld unit is 0.6 by 0.01m. The sensor was passed over the entire plot area and an average NDVI was determined from all readings taken (approximately 15 readings per plot). The sensor outputs an NDVI value at a rate of 10 readings per second. The sensor was held at height of approximately 0.9 m above the crop canopy.

In 2002 the INSEY equation used was $YP_0 = 365.85329 \times \exp(-INSEY/-0.0035267288)$. For the 2003 this equation was updated to $YP_0 = (0.5005 \times \exp(INSEY \times 267.65)) \times 1000$. The updates in the 2003 algorithm reflect the additions of data collected the previous growing season into the estimated yield potential database.

An RI based on NDVI ($RI_{NDVI}$) was determined by taking sensor readings in the induced non-N-limiting plots (preplant application of 90 kg N $ha^{-1}$) and dividing by the check plots (0 N). $RI_{SV}$ was calculate from NDVI readings of treatments one thru five, using the same NDVI readings taken for calculating topdress rates using the NFOA algorithms. These treatments had zero additions of N fertilizer either preplant or topdress when the sensor readings were taken. This allowed for simulation of NDVI taken from 20 randomly selected 1.5 $m^2$ field element sizes in the same field. The NDVI of 20 plot means (5 treatments x 4 replications = 20) were used to calculate an overall average, and a standard error. There by, $RI_{SV}$ = (Overall mean NDVI + 1 Standard error) / (Overall mean NDVI - 1 Standard error).

$RI_{PLANTHEIGHT}$ was determined using the same treatments as $RI_{NDVI}$. Plant height was measured with a meter stick, and recording the length of extended leaves to the nearest millimeter. Measurements were taken by setting the meter stick next to the wheat plant and height was figured from extending the leaves along the ruler. Five measurements were taken from each plot and a mean was figured for each to the two treatments used to determine the response index.

All preplant treatments used ammonium nitrate (34-0-0) as the fertilizer N source. Preplant treatments will be incorporated by hand using a rake after application. All topdress rates used urea-ammonium nitrate solution (28-0-0), applied with a hand held variable rate sprayer developed at Oklahoma State University. All sites were planted in a 19cm row spacing using a Tye® small grain drill except for the Tipton 2003 site, which was planted in a 25cm row spacing. A light tillage operation, using a field cultivator, was used on an as needed basis prior to planting for weed control.

All plots were harvested by hand, removing the center 1m$^2$ from of each plot. All plots were cut at ground level, and dry weights taken before grain was threshed. Sub samples were taken of the straw and grain for total nitrogen analysis using a Carlo-Erba NA-1500 dry combustion analyzer (Schepers et al., 1989). All sub samples were dried and ground to pass a 140-mesh sieve (100 µm). All statistical analysis was completed using SAS (SAS Institute, 2000).

## RESULTS

### Crop Year 2001-2002

At three sites (Efaw Bottom, Marshall and Kingfisher) $RI_{NDVI}$ was less than or near 1.1 indicating that it would be unlikely to observe a response to topdress applied N. This was confirmed at harvest with no significant differences between grain yields in the check (0 N) and those treatments that received topdress N at these same sites (Efaw Bottom, Marshall and Kingfisher) (Table 4). Not surprisingly, applying no N was the most profitable management scheme at the non-N-responsive sites (Table 5). This supported the fact that producers need to start reducing preplant N rates, to be able to capitalize on years where little to no N is needed to reach maximum profitability per hectare, which would have only been recognizable by having the N-rich strip.

Within the same three non-responsive sites, most of the N treatments resulted in low NUE's. Treatments five to eight represents traditional N management practices used today. These findings support the fact that NUE in a typical winter wheat production system can be quite low. In addition, this illustrates that managing N fertilizer recommendations based on an in-season estimate of RI needs to be extended to producers. By using an in-season RI producers can adjust N recommendations for temporal variation.

At the two remaining sites, $RI_{NDVI}$ indicated additional N could achieve an increase in grain yield. Topdress N did significantly increase yields at the Efaw upland location, but did not at the Hennessey site (Table 4). At the Efaw upland site, supplying topdress N at lower rates (forage NFOA and grain NFOA) resulted in the same yield level as the 90 kg N $ha^{-1}$ treatment. Supplying, on average, 61 kg N $ha^{-1}$ as a topdress application (2x grain NFOA,) resulted in similar yield levels to that of applying 45 kg $ha^{-1}$ N preplant and 45 kg $ha^{-1}$ N as a topdress (Table 4). The response to in-season applied N at this site, as indicated by $RI_{NDVI}$ is encouraging and helps to support the need for managing N for temporal variability. More over, this supports the theory winter wheat can recover from N stress encountered early in the growing season and still achieve maximum yield while improving profitability, even when application date may be past optimum (Boman et. al. 1995)

It is important to note that the Marshall site had the lowest preplant soil nitrate test level at 12 mg $kg^{-1}$ $NO_3$-N $ac^{-1}$ and had a low RI and no response to mid season N fertilizer (Table 4). This suggests that preplant soil test $NH_4$-N and $NO_3$-N data can be unreliable because it does not integrate weather conditions that are actually encountered and that lead to increased and/or decreased plant available N from soil organic sources or rainfall. Using current methods to determine preplant N recommendations, this site was the most deficient in inorganic nitrogen and a response to N fertilizer would be likely. Based on the response index and the yield of the check (0 N) treatment, this was obviously not the case (Table 4). This strengthens the argument that soil testing to determine N need is a static measure of a dynamic system which not reliably predict how the crop will respond to applied N (Walley et. al. 2002).

## Results: Crop Year 2002-2003

It is important to note that the Tipton site experienced a hard freeze on April 9, 2003, a full month after topdress application of N fertilizer. The Tipton site had an $RI_{NDVI}$ of 1.15 suggesting response to additional N would be likely. The highest grain yielding treatment was four, which received 72 kg N $ha^{-1}$ of topdress N. Grain yield of treatment four was not statistically different from the grain yield of treatment six which received 45 kg N $ha^{-1}$ preplant and 45 kg N $ha^{-1}$ topdress (Table 6). Since, yield has the greatest impact on profitability, treatment four had the most return with respect to N management. It was apparent that treatments with preplant N were more susceptible to damage from a late freeze than those that received all N mid season (Alcoz et. al. 1993).

The $RI_{NDVI}$ at the Efaw Upland site indicated that there would be a large response ($RI_{NDVI}$ = 1.48) to additional N at time of application of topdress N (Feekes 4-6). Topdress N did significantly improve grain yields (Table 6). There was no difference in grain yields when the total amount on N applied was greater than 75 kg N $ha^{-1}$. Applying all N or a large portion of it preplant and topdressing with smaller amounts did result in higher profits than applying a large amount of N midseason (zero preplant) (Table 7). Yields were significantly less with limited difference between grain yields, when total N amounts applied were less than 60 kg N $ha^{-1}$.

The $RI_{NDVI}$ predicted that response to additional N would be small ($RI_{NDVI}$ = 1.06) at the Perkins site. The application of only 4 kg N $ha^{-1}$ topdress N produced a grain yield that was no different than any other N treatment. This site is classified as a responsive site because there was a difference in the grain yield of when 45 kg N $ha^{-1}$ preplant plus 45 kg N $ha^{-1}$ topdress was applied compared with the check (0 N) treatment. However, there was no difference in return on N management from any treatment. This helps support the fact that if $RI_{NDVI}$ indicates a site will have little response to additional N, a farmer can forgo making additional investments in applying N and still achieve maximum profitability ($p$ value $<0.05$).

The Lake Carl Blackwell (L.C.B.) site had an $RI_{NDVI}$ of 1.27, indicating that there would be a response to additional N. This was observed with an increase in grain yields over 1500 kg $ha^{-1}$ for some N treatments. However, limited differences between N treatments were found, excluding those where N rate was less than 45 kg N ha$^{-1}$. In general either applying all N preplant or applying a large quantity mid-season (no preplant) resulted in the highest grain yields and profit (Tables 6 and 7).

## DISCUSSION

Based on two years and 9 experimental sites over eight different locations, the degree of response to N varied by year and location (Figure 1). This implies a need for N recommendations to have the flexibility to encompass temporal variations at different locations. $RI_{NDVI}$ was a good indicator of a sites potential responsiveness to additional N. Across nine sites, different environments and two years $RI_{NDVI}$ was positively correlated with $RI_{Harvest}$ ($RI_{Harvest} = 3.9365(RI_{NDVI}) - 3.2639$, $r^2 = 0.75$) (Figure 1). The slope of this line is greater than that reported by Mullen et. al. (2003) which was $RI_{Harvest} = 1.06(RI_{NDVI}) + 0.18$ .

However, looking at that set of data, six of the points for both $RI_{NDVI}$ and $RI_{HARVEST}$ are below 1.25 and 1.26 respectively. This is encouraging even as it shows that if $RI_{NDVI}$ indicates that a site might be marginally responsive to additional N, it is confirmed with the low $RI_{HARVEST}$. A site was considered non-responsive if the $RI_{NDVI}$ is from 1.0 to 1.10 and marginally responsive from >1.10 <1.25. At the marginally responsive range the increase in grain yield from additional N may not have an economical return on the expenditure for the N fertilizer. In the non-responsive range it is very unlikely that the producer would observe an economic return on the N fertilizer dollar spent to obtain the small increase in grain yield.

It was somewhat interesting to note that the slope of $RI_{NDVI}$ verses $RI_{HARVEST}$ is not close to 1.0. Lukina et. al (2001) found that at Feekes 4-6, winter wheat had taken up in the forage 45 kg N ha$^{-1}$. This amount represented over half of the total N that would be in the grain at harvest. So, at early growth stages, winter wheat has taken up a large portion of the N that the plant needs to meet its yield potential. Thus, one would expect that the relationship between the response indices would be very similar to and would have a slope of one.

If a site is not responsive to additional N then a priming effect (Westerman and Kurtz, 1973; Ma. B.L. et al, 1999) will not be observed, as there is already enough non- fertilizer N available to meet the needs of the developing crop to maturity. At a site that is responsive or predicted to be responsive, then there is a lack of N to meet the needs of the biological activity therefore; additional fertilizer N added maybe immobilized and reduces nitrogen use efficiency of topdress N applications.

$RI_{PLANTHEIGHT}$ over all nine locations was strongly correlated with $RI_{HARVEST}$ ($r^2 = 0.74$) (Figure 2). This is very encouraging findings as this allows for producers to make a reliable estimate of $RI_{HARVEST}$ without the use of a handheld sensor. This could be very useful to producers in developing countries that farm only a few hectares and can not afford a hand held sensor, but can still capitalize on the use of managing N for temporal variability by using a N-rich strip (area) and compare to the farmer practice of the rest of the field. $RI_{PLANTHEIGHT}$ was slightly correlated with $RI_{NDVI}$ over nine sites and two years ($r^2 = 0.61$) (Figure 3, Tables 8 and 9).

$RI_{SV}$ was poorly correlated with both with $RI_{HARVEST}$ and $RI_{NDVI}$ (Figures 4 and 5). The failure of $RI_{SV}$ to predict $RI_{HARVEST}$ or estimate $RI_{NDVI}$ could be due to not enough random field element size of <1.5m$^2$ measured in this study. Further investigation is needed to determine how many field element size of < 1.5 m$^2$ would be needed to reliably predict and estimate both $RI_{HARVEST}$ and $RI_{NDVI}$ , respectively in a given field. In addition $RI_{SV}$ assumes that the variability measured by the sensor is due to spatial difference in N. $RI_{SV}$ should be measured only when a crop stand visually appears uniform, and is not affected any other factors that could attribute to the variation in NDVI measured in a random field elements. Factors that could contribute the failure of $RI_{SV}$ to predict $RI_{HARVEST}$ could be but not limited to the following: uneven plant stands, variations in tiller density, differences in plant available water in the soil solution, drainage, degree and direction of facing slope. Any soil parameter that affects the growth of the crop other than N status of the soil from one field element to another would make $RI_{SV}$ an unreliable estimate of the crops potential responsiveness to additional N.

In-season N management schemes that incorporate an in-season response index ($RI_{NDVI}$ or $RI_{PLANTHEIGHT}$) will allow for producers to quantify the likelihood of achieving an economical response to addition N, tailored to that site, for that growing season. If producers are to realize full potential of this system, preplant N rates must be reduced. By reducing preplant N rates they can start to take advantage of years where little or no N is needed to achieve maximum yields and profitability on N management. This helps support the effectiveness of using a sensor based approach for making N recommendations over the current industry standard of yield goals and preplant soil samples for residual nitrate. Even if producers do not treat with in field spatial variability, the use of an N-rich strip and a check will allow them to adjust for temporal variability, and large-scale variability (by field). This will help to improve their NUE over current N management practices.

Averaged over all nine sites, treatment four had the highest profitability (Table 10). This is important to note because it reflects the ability of a single application of N mid-season and that it recovered 100 percent of maximum yield. Because this treatment was essentially double that of treatment three, but using a nitrogen use efficiency factor of 35 percent instead of 70 percent, respectively, it supports that assuming the need for decreasing nitrogen use efficiency actually. Topdress N applications have a more realistic nitrogen use efficiency near 50 percent or less.

For non-N-responsive sites NUE is generally poor. Simply because the crop did not utilize the additional N, thus reducing NUE. However, at two responsive sites increased NUE was observed with small amounts topdress N (Efaw upland 2001-2002, and Perkins 2002-2003). Both of these sites had NUE's above 100 percent for treatments that received less than 15 kg N ha$^{-1}$ N applied topdress (Figures 6 and 7). This is somewhat consistent with the priming effect, in which small amounts of fertilizer can encourage N mineralization in field conditions, as was also observed by Westerman and Kurtz, (1973) and Ma, B.L. et. al (1999). These two papers demonstrated that additions of fertilizer N enhance the mineralization process. It was believed to be the increased microbial activity in the soil, which contributed to increased N mineralization (Franzluebbers et. al. 1994).

NUE of a flat rate of N applied either preplant or topdress is thought to increase as a site's responsiveness to N increases (Johnson and Raun, 2003). This is based on the idea that as plant demand for N becomes greater the use efficiency of the N applied will increase. This relationship was observed for the 90 kg N $ha^{-1}$ preplant, 45 kg N $ha^{-1}$ preplant and 45 kg N $ha^{-1}$ topdress (Figures 8 thru 10). The NUE's increased from 0 to 40 percent with increasing $RI_{HARVEST}$ values from 1.0 to ~1.5 and the percent increase in grain yield of 0 to 68 percent for 90 kg N $ha^{-1}$ preplant. Then there is not an increase in NUE between $RI_{HARVEST}$ values 1.5 to nearly 3.0. Yet, there was nearly a 200 percent increasing in grain yield.

The same effect is observed for the 45 kg N $ha^{-1}$ applied preplant treatment across $RI_{HARVEST}$ except for the Perkins site. At this site NUE reached its maximum value of 51 percent at the $RI_{HARVEST}$ value of 1.26, then declined and leveled off between $RI_{HARVEST}$ values of 1.5 and 3.0 with NUE around 30 percent. NUE of 45 kg N $ha^{-1}$ applied topdress leveled off at 45 percent with an increase in grain yield from 55 to 125 percent (Figure 11). This can be explained by the fact the increase in grain yield is offset by a decrease in the amount of N in grain (Tables 11 and 12). On average, the NUE of the 45 kg N $ha^{-1}$ applied topdress is slightly higher than of the same amount of N applied preplant.

The unaccounted for N could have been subject to losses of denitrification, immobilization, volatilization, or by the plant itself. The plant itself is extremely inefficient in translocating N from vegetative parts of the plant to grain, even when it is showing a strong response in terms of grain yield. Plant inefficiencies have been well documented by other researchers (Reddy and Reddy, 1993; Kanampiu et. al., 1997; Francis et. al., 1993; Thomason W.E., 1996). Reddy and Reddy reported that N unaccounted for in the soil-plant system was nearly three times higher when fertilizer N application increased from 100 to 200 kg N $ha^{-1}$ for maize. They concluded that the unaccounted N was lost to leaching below the root zone or by denitrification. Even so, they indicated that they had to irrigate the crop three times during the growing season due to drought conditions. Thus, it is hard to believe that the N was actually moved below the root zone. However, they did illustrate that only 9 to 17 percent of the labeled $^{15}N$ in various plant parts was translocated into the grain and that NUE ranged from 43 to 57 percent for maize in the Piedmont region. Francis et. al. (1993) reported that nearly 52 to 73 percent of the unaccounted for N using $^{15}N$ could be attributed to plant loss after anthesis in maize.

Kanampiu et. al (1997) found that in winter wheat, loss of N by the plant was greatest for a period between anthesis and 14 days after anthesis. Kanampiu et. al. estimated that N losses from the amount accumulated in plants at anthesis and that amount still remaining at harvest ranged from 7.7 to 59.4 percent over a two year period, two locations and different N rates. Thomason (1996) reported that the NUE of applying 90 kg N $ha^{-1}$ preplant for a forage production system using winter wheat was 77 percent, with the NUE at harvest for the grain production system was only 31 percent.

Increasing the amount of N applied decreased NUE, even though there was a response increase in grain yield. As N rate increased, NUE went down when method of application (either all preplant or all topdress) were the same (Figures 7,8,12). An example of this is the response of treatment four at the Lake Carl Blackwell site, which received 119 kg N $ha^{-1}$ topdress only. This N rate resulted in an increase in grain yield of 81 percent and the NUE was 40 percent. At the same site 45 and 65 kg N $ha^{-1}$ topdress only, had the same percent increase in grain yield yet, the NUE was the same as the 119 kg N $ha^{-1}$ topdress only treatment. More over, the Efaw upland site for the 2002-2003 was the most responsive encountered in this study. Even at this site, with a $RI_{HARVEST}$ of 2.99, applying 93 kg N $ha^{-1}$ topdress increased grain yield over 180 percent and had the same NUE as applying 23 and 45 kg N $ha^{-1}$ in a topdress application. This supports the fact that N in grain decreases as grain yields increases (Tables 11 and 12).

Knowing that plant N losses could be a large source of unaccounted for N in N budgets, even when there is a large response to additional N, total N uptake by the plant could be quite higher than what was reported by NUE. Future evaluations made about trying to increase NUE by N management should also take into consideration that plant losses of N could be very substantial. This could be accomplished by taking a forage sub-sample of a respective treatment at the time of anthesis and measuring total N uptake in above ground biomass.

Or, by a non-destructive method using sensors to estimate total N uptake, which would allow for a reliable to measure total N uptake by the plant (Stone et al 1996 a, b; Sembiring et. al. 1998; Osborne et. al. 2002). In addition, a harvest soil sample of the rooting depth to account for residual soil organic and inorganic N. By doing so would allow for determination as to which part of the system (either the plant or the soil) is the causing the greatest decrease in nitrogen use efficiency.

## CONCLUSION

The driving factor for adaptation of this technology will be profitability and the risk for reliance on topdress application of the crop N needs. With review of work previously done by Boman et. al., which showed that the optimum time for applying N is January to February in this region (Oklahoma). Even when delaying N application till early to mid March, the Efaw upland site for both years treatment 4 (2 x Grain NFOA) was able to obtain maximum grain yields with applying all N in a single topdress application. At this site treatment four had the highest grain yield in 2001-2002 and was not significantly less than the highest grain yielding (treatment six) for 2002-2003 (p value $\leq$ 0.05). This illustrates that maximum yields can be achieved by delaying N applications of N stressed winter wheat till Feekes 6. This should reduce producers risk exposure with respect to yield loss by early season N stresses and delaying N application till later in the growing season.

By including costs for both traditional N management and sensor-based technology for N management, comparison showed the sensor-based technology

N management schemes performed as well if not better then traditional N management. The sensor-based technology could have saved producers from incurring additional N cost when there would not have been an economical response to the additional N on three non-responsive sites. Averaged over 9 sites treatment four recovered 100 percent of yield and achieved the highest profitability. This supports the idea that sensor based approaches to N management perform as well as traditional N management schemes.

The major reason that the grain NFOA only (treatment 3) at responsive sites failed to reach maximum yield and profitability was due to the under prediction of $RI_{HARVEST}$ and over estimating the use efficiency of fertilizer N. Under estimating the actual response to N and/or over estimating the use efficiency of fertilizer N is a critical error in this N management system for achieving maximum grain yield with zero preplant. With review of the data obtained in this study, when a site is highly responsive to additional N, NUE of economical yield levels was under 50 percent, indicating that N recommendations should divided by an efficiency factor $\leq 0.5$ instead of 0.7. This implies that the use efficiency will only be 50 percent. Timely N applications and improvements in the ability to predict $RI_{HARVEST}$, and using a use efficiency that does not over estimate the actual fertilizer N use efficiency, will greatly enhance the effectiveness of this approach for N management to achieve maximum yield and profitability.

$RI_{NDVI}$ was related to $RI_{HARVEST}$ over 9 locations and two years. Use of the response index will allow producers to move away from reliance on preplant application of N and to start managing N based on the likelihood of achieving an economical response to N fertilizer. This can only be done when a non-N-limited area is installed and the N management practice allows for N rates to be adjusted by season and location.

$RI_{PLANTHEIGHT}$ can be a very useful tool for small farmers in developing countries, managing small tracts or those in developed countries managing larger tracts of land, that cannot or do not want to initially undergo the cost of a handheld sensor, till the producer becomes comfortable with this style of N management. Furthermore, $RI_{PLANTHEIGHT}$ should continue to be evaluated as a potential aid when using $RI_{NDVI}$. An example could be at a site where $RI_{NDVI}$ has indicated that it would be marginal in its response to additional N, could be confirmed with the $RI_{PLANTHEIGHT}$. The fact that $RI_{PLANTHEIGHT}$ was strongly correlated with $RI_{HARVEST}$ indicates that it can be used instead of $RI_{NDVI}$. Yet, the N recommendations used in this study rely solely on information derived from the sensors to generate NDVI. Thus, $RI_{NDVI}$ is still a reliable tool that should be used because the measurements easy and rapid. For a producer that has many fields to evaluate in a short time, taking 40 to 50 plant measurements per site, with a meter stick, and then calculating averages from the data collected could take up valuable time and labor.

$RI_{SV}$ should not be used to determine $RI_{NDVI}$ or $RI_{HARVEST}$. Of the three response indices for predicting a site's potential responsiveness to N, this was the poorest. Part of the problem in this study was possible lack of data collected to obtain enough samples of the total population with the field. Also, this response index assumes that the variability measured by the sensor is due to N status of the soil alone. That can be a risky assumption when all the possible factors that could be affecting the measured variability are examined.

The algorithms used in this study looked only at maximizing yield and not on maximizing profitability. The current algorithms could be retro fitted to recommend N not based on maximizing yield but maximizing profitability. Assuming that the value of the marginal increase in grain yields at $YP_N$ is less than the marginal increase in the cost of additional N needed to reach $YP_N$, then maximum profitability would lie between the range of $YP_0$ and $YP_N$. Then the fertilizer N recommendation for a site would be where the estimated value of the increase in the grain yield equals the value of the additional cost of N needed to reach that increase in yield ($YP_{PROFIT}$). This is based on the economical principle of law of diminishing returns; where input should be add till the value of each additional output unit equals the cost of the each additional unit of input. The N recommendation would then be (grain N uptake at $YP_{PROFIT}$ minus the grain N uptake at $YP_0$) / (fertilizer N use efficiency factor)). This would base N rate recommendations based on maximizing net return instead of yield.

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Table 1: Surface (0-15 cm) soil test data by location for 2001-2003 prior to experiment establishment.

2001-2002 crop year sites

| Location | $NH_4$-N | $NO_3$-N | P | K | pH |
|---|---|---|---|---|---|
| | mg $kg^{-1}$ | | | | |
| Marshall | 8 | 12 | 20 | 273 | 5.6 |
| Classification: Kirkland silt loam; Fine, mixed, thermic, Vertic Paleustolls | | | | | |
| Hennessey | 6 | 20 | 35 | 199 | 5.5 |
| Classification: Pond Creek silt loam 1-3% slopes; Fine silty, mixed, thermic, Udic Argiustolls | | | | | |
| Kingfisher | 6 | 17 | 41 | 292 | 5.8 |
| Classification: fine, mixed, thermic, Vertic Paleustolls | | | | | |
| Efaw upland | 8 | 13 | 26 | 164 | 5.4 |
| Classification: Norge soil series: Fine-silty, mixed, thermic Udic Paleustolls | | | | | |
| Efaw Bottom | 7 | 39 | 36 | 186 | 6.3 |
| Classification: Easpur soil series: Fine -Loamy, mixed, thermic Fluventic Haplustolls | | | | | |

2002-2003 crop year

| Location | $NH_4$-N | $NO_3$-N | P | K | pH |
|---|---|---|---|---|---|
| | mg $kg^{-1}$ | | | | |
| Tipton | 5 | 9 | 24 | 324 | 6.36 |
| Classification: Tipton silt loam : fine-loamy, mixed, thermic, Pachic Urgiustoll | | | | | |
| Perkins | 3 | 12 | 15 | 146 | 5.47 |
| Classification: Teller sandy loam: fine-loamy, mixed, thermic Udic Argstoll | | | | | |
| Lake Carl Blackwell | 3.35 | 10 | 18 | 107 | 5.28 |
| Classification: Port-oscar: silt loam, fine-silty, mixed, super active, thermic Cumulic Haplustolls | | | | | |

† Composite soil samples were taken at random from the site area before any fertilizer was applied

‡ $NH_4$-N and $NO_3$-N – 2 *M* KCl extraction

§ P and K – Mehlich III extraction

# pH – 1:1 soil:water

Table 2: Dates of field activities, seeding rates and varieties planted for 2001-2002 crop year.

| | Location | | | | |
|---|---|---|---|---|---|
| | Efaw Upland | Efaw Bottom | Hennessey | Marshall | Kingfisher |
| Pre-Plant Fertilization Date | 24/09/01 | 28/09/01 | 20/09/01 | 20/09/01 | 20/09/01 |
| Planting Date (dd/mm/year) | 01/10/01 | 04/10/01 | 19/10/01 | 19/10/01 | 01/10/01 |
| Variety | Jagger | Custer | Jagger | Jagger | Jagger |
| (Seeding Rate Lbs$^{-1}$ac) | (90 kg$^{-1}$ha) | (90 kg$^{-1}$ha) | (90 kg$^{-1}$ha) | (90 kg$^{-1}$ha) | (100 kg$^{-1}$ha) |
| Sensing Date | 11/03/02 | 11/03/02 | 28/03/02 | 28/03/02 | 28/03/02 |
| Days from Planting to Sensing (GDD > 0) | 109 | 106 | 101 | 101 | 124 |
| Topdress Fertilization Date | 13/03/02 | 13/03/02 | 29/03/02 | 29/03/02 | 29/03/02 |
| Harvest Date | 07/06/02 | 07/06/02 | 07/06/02 | 07/06/02 | 07/06/02 |

Table 3: Dates of field activities, seeding rates and varieties planted for 2002-2003 crop year.

| | Location | | | |
|---|---|---|---|---|
| | Efaw Upland | Tipton | Perkins | Lake Carl Blackwell |
| Pre-Plant Fertilization Date (dd/mm/year) | 04/09/02 | 17/09/02 | 12/09/02 | 05/09/02 |
| Planting Date (dd/mm/year) | 05/10/02 | 26/09/02 | 14/10/02 | 01/10/02 |
| Variety | 2174 | Custer | Jagger | Jagger |
| (Seeding Rate Lbs$^{-1}$ac) | (90 kg$^{-1}$ha) | (80 kg$^{-1}$ha) | (90 kg$^{-1}$ha) | (90 kg$^{-1}$ha) |
| Sensing Date (dd/mm/year) | 07/03/03 | 06/03/03 | 12/03/03 | 07/03/03 |
| Days from Planting to Sensing (GDD > 0) | 92 | 115 | 91 | 99 |
| Topdress Fertilization Date | 07/03/03 | 06/03/03 | 12/03/03 | 07/03/03 |
| Harvest Date | 30/05/03 | 29/05/03 | 30/05/03 | 26/05/03 |

Table 4: Yield and nitrogen use efficiency at five sites for 2001-2002.

| | | | Location | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Efaw upland | | Efaw bottom | | Hennessy | | Marshall | | Kingfisher | |
| | Preplant N | Topdress N | Grain Yield | NUE | Grain Yield | NUE | Grain Yield | NUE | Grain Yield | NUE | Grain Yield | NUE |
| Trt # | ---------kg ha$^{-1}$------- | | kg ha$^{-1}$ | % | kg ha$^{-1}$ | % | kg ha$^{-1}$ | % | kg ha$^{-1}$ | % | kg ha$^{-1}$ | % |
| 1 | 0 | 0 | 1305 | | 2361 | | 2467 | | 2792 | | 3167 | |
| 2 | 0 | Forage NFOA | 1710 (13) | 101 | 2618 (14) | 56 | 2255 (14) | 0 | 2134 (2) | 0 | 2785 (0) | 0 |
| 3 | 0 | Grain NFOA | 1877 (10) | 118 | 1831 (4) | 0 | 2406 (12) | 0 | 2285 (3) | 78 | 2391 (1) | 0 |
| 4 | 0 | 2X Grain NFOA | 2633 (61) | 52 | 2508 (69) | 9 | 2860 (66) | 8 | 2800 (29) | 17 | 3076 (65) | 9 |
| 5 | 0 | 45 | 2013 | 38 | 2554 | 22 | 2452 | 0 | 2694 | 5 | 3072 | 5 |
| 6 | 45 | 45 | 2508 | 25 | 2656 | 8 | 2599 | 7 | 2981 | 6 | 3133 | 9 |
| 7 | 45 | 0 | 1986 | 27 | 2421 | 15 | 2134 | 0 | 2981 | 13 | 3360 | 26 |
| 8 | 90 | 0 | 1573 | 7 | 2482 | 10 | 2255 | 2 | 2921 | 5 | 2962 | 4 |
| 9 | 45 | Grain NFOA | 1986 (11) | 24 | 2452 (4) | 20 | 2785 (12) | 14 | 2331 (3) | 4 | 2894 (1) | 5 |
| | | SED | 245 | 24 | 172 | 13 | 173 | 4 | 264 | 33 | 211 | 8 |
| | $RI_{PLANT\ HEIGHT}$ | | 1.15 | | 1.21 | | 1.08 | | 1.03 | | 1.01 | |
| | $RI_{NDVI}$ | | 1.27 | | 1.06 | | 1.23 | | 1.11 | | 1.01 | |
| | $RI_{SV}$ | | 1.41 | | 1.14 | | 1.37 | | 1.4 | | 1.04 | |
| | $RI_{HARVEST}$ | | 1.57 | | 1.06 | | 0.92 | | 1.07 | | 1.06 | |

† Numbers in parentheses indicates the average amount of topdress N applied in kg$^{-1}$ ha.

‡ NUE is calculated as: (Grain N uptake of N treatment – Grain N uptake + Straw N uptake of check) / (Total amount of N applied).

§ SED- Standard error of the difference between two equally replicated means

¶ $RI_{PALNT\ HEIGHT}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8 / Plant height of treatment 1)

\# $RI_{NDVI}$ = Response index measured in-season using NDVI readings (NDVI treatment 8 / NDVI treatment 1)

†† $RI_{SV}$ = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED) / (mean NDVI – 1SED))

‡‡ $RI_{HARVEST}$ = Response index measured using highest grain yield of a preplant N treatment only divided by grain yield of treatment 1

§§ NFOA- Nitrogen Fertilizer Optimization Algorithm

Table 5: Economical analysis of nitrogen management at five sites for 2001-2002.

| | | | Location | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Efaw upland | | Efaw bottom | | Hennessy | | Marshall | | Kingfisher | |
| | Preplant N | Topdress N | Net Ret. N Mgt | Cost of N Mgt. | Net Ret. N Mgt | Cost of N Mgt. | Net Ret. N Mgt | Cost of N Mgt. | Net Ret. N Mgt | Cost of N Mgt. | Net Ret. N Mgt | Cost of N Mgt. |
| Trt # | ----------kg $ha^{-1}$---------- | | $ $ha^{-1}$ | $ $ha^{-1}$ | $ $ha^{-1}$ | $ $ha^{-1}$ | $ $ha^{-1}$ | $ $ha^{-1}$ | $ $ha^{-1}$ | $ $ha^{-1}$ | $ $ha^{-1}$ | $ $ha^{-1}$ |
| 1 | 0 | 0 | 144 | 0 | 260 | 0 | 272 | 0 | 308 | 0 | 349 | 0 |
| 2 | 0 | Forage NFOA | 169 | 19 | 268 | 20 | 228 | 20 | 222 | 13 | 294 | 12 |
| 3 | 0 | Grain NFOA | 189 | 18 | 187 | 14 | 246 | 19 | 238 | 14 | 251 | 13 |
| 4 | 0 | 2X Grain NFOA | 244 | 46 | 226 | 50 | 266 | 49 | 280 | 28 | 291 | 48 |
| 5 | 0 | 45 | 189 | 32 | 249 | 32 | 238 | 32 | 264 | 32 | 306 | 32 |
| 6 | 45 | 45 | 217 | 60 | 232 | 60 | 227 | 60 | 269 | 60 | 285 | 60 |
| 7 | 45 | 0 | 191 | 28 | 238 | 28 | 207 | 28 | 301 | 28 | 342 | 28 |
| 8 | 90 | 0 | 130 | 43 | 230 | 43 | 206 | 43 | 279 | 43 | 284 | 43 |
| 9 | 45 | Grain NFOA | 173 | 46 | 227 | 42 | 260 | 46 | 215 | 41 | 278 | 40 |
| | | SED | 26 | 3 | 19 | 2 | 19 | 2 | 29 | 1 | 23 | 1 |

| | Efaw upland | Efaw bottom | Hennessy | Marshall | Kingfisher |
|---|---|---|---|---|---|
| $RI_{PLANT\ HEIGHT}$ | 1.15 | 1.21 | 1.08 | 1.03 | 1.01 |
| $RI_{NDVI}$ | 1.27 | 1.06 | 1.23 | 1.11 | 1.01 |
| $RI_{SV}$ | 1.41 | 1.14 | 1.37 | 1.4 | 1.04 |
| $RI_{HARVEST}$ | 1.57 | 1.06 | 0.92 | 1.07 | 1.06 |

† Net Return on N Management: assumed ($0.11 $kg^{-1}$ wheat – Cost of N Management).

‡ Cost of N Management assumed: Preplant N of $0.33 $kg^{-1}$ with $12.35 $ha^{-1}$ application cost and 2.5% interest on preplant costs. Topdress N assumed $0.55 $kg^{-1}$ with application costs of $7.41 $ha^{-1}$. Treatments with variable rates assumed an additional technology fee of $4.94 $ha^{-1}$.

§ SED- Standard error of the difference between two equally replicated means

¶ $RI_{PALNT\ HEIGHT}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8 / Plant height of treatment 1)

\# $RI_{NDVI}$ = Response index measured inseason using NDVI readings (NDVI treatment 8 / NDVI treatment 1)

†† $RI_{SV}$ = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED) / (mean NDVI – 1SED))

‡‡ $RI_{HARVEST}$ = Response index measured using highest grain yield of a preplant N treatment only divided by grain yield of treatment 1

§§ NFOA- Nitrogen Fertilizer Optimization Algorithm

Table 6: Yield and nitrogen use efficiency at four sites for 2002-2003.

| | | | Location | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Efaw | | Tipton† | | Perkins | | Lake Carl Blackwell | |
| Trt # | Preplant N | Topdress N | Grain Yield | NUE | Grain Yield | NUE | Grain Yield | NUE | Grain Yield | NUE |
| | ----------kg $ha^{-1}$---------- | | kg $ha^{-1}$ | % | kg $ha^{-1}$ | % | kg $ha^{-1}$ | % | kg $ha^{-1}$ | % |
| 1 | 0 | 0 | 830 | | 698 | | 2757 | | 2435 | |
| 2 | 0 | Forage NFOA | 1848 (59) | 33 | 978 (54) | 16 | 3363 (47) | 40 | 3530 (65) | 36 |
| 3 | 0 | Grain NFOA | 1223 (23) | 37 | 735 (7) | 20 | 3235 (4) | 285 | 3117 (22) | 31 |
| 4 | 0 | 2X Grain NFOA | 2355 (93) | 40 | 1326 (72) | 25 | 3330 (71) | 31 | 4417 (119) | 41 |
| 5 | 0 | 45 | 1845 | 43 | 958 | 16 | 3393 | 40 | 3605 | 45 |
| 6 | 45 | 45 | 2900 | 43 | 1260 | 17 | 3698 | 33 | 4143 | 35 |
| 7 | 45 | 0 | 1613 | 29 | 793 | 6 | 3583 | 51 | 3037 | 20 |
| 8 | 90 | 0 | 2480 | 32 | 630 | 0 | 3480 | 23 | 4083 | 36 |
| 9 | 45 | Grain NFOA | 2457 (31) | 39 | 750 (7) | 3 | 3373(4) | 28 | 3503 (24) | 27 |
| | | SED | 158 | 7 | 103 | 7 | 242 | 68 | 190 | 8 |
| | $RI_{PLANT\ HEIGHT}$ | | 1.65 | | 1.18 | | 1.02 | | 1.12 | |
| | $RI_{NDVI}$ | | 1.48 | | 1.15 | | 1.06 | | 1.27 | |
| | $RI_{SV}$ | | 1.39 | | 1.52 | | 1.7 | | 1.25 | |
| | $RI_{HARVEST}$ | | 2.99 | | 0.90 | | 1.26 | | 1.68 | |

† Tipton site experienced a late freeze on April 9, 2003

‡ Numbers in parentheses indicates the average amount of topdress N applied for variable rate treatments

§ NFOA- Nitrogen Fertilizer Optimization Algorithm

¶ SED- Standard error of the difference between two equally replicated means

\# NUE is calculated as: (Grain N uptake of N treatment – Grain N uptake of check) / (Total amount of N applied).

†† $RI_{PALNT\ HEIGHT}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8 / Plant height of treatment 1)

‡‡ $RI_{NDVI}$ = Response index measured in-season using NDVI readings (NDVI treatment 8 / NDVI treatment 1)

§§ $RI_{SV}$ = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED) / (mean NDVI – 1SED))

¶¶ $RI_{HARVEST}$ = Response index measured using highest grain yield of a preplant N treatment only divided by grain yield of treatment 1

Table 7: Economical analysis of nitrogen management at four sites for 2002-2003.

| | | | Location | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Efaw | | Tipton | | Perkins | | Lake Carl Blackwell | |
| | Preplant N | Topdress N | Net Ret. | Cost | Net Ret. | Cost | Net Ret. | Cost | Net Ret. | Cost |
| Trt # | ----------kg $ha^{-1}$---------- | | \$ $ha^{-1}$ | \$ $ha^{-1}$ | \$ $ha^{-1}$ | \$ $ha^{-1}$ | \$ $ha^{-1}$ | \$ $ha^{-1}$ | \$ $ha^{-1}$ | \$ $ha^{-1}$ |
| 1 | 0 | 0 | 91 | 0 | 77 | 0 | 303 | 0 | 268 | 0 |
| 2 | 0 | Forage NFOA | 158 | 45 | 66 | 42 | 332 | 38 | 340 | 48 |
| 3 | 0 | Grain NFOA | 109 | 25 | 65 | 16 | 341 | 14 | 319 | 24 |
| 4 | 0 | 2X Grain NFOA | 195 | 64 | 94 | 52 | 315 | 51 | 408 | 78 |
| 5 | 0 | 45 | 171 | 32 | 73 | 32 | 341 | 32 | 364 | 32 |
| 6 | 45 | 45 | 259 | 60 | 79 | 60 | 347 | 60 | 396 | 60 |
| 7 | 45 | 0 | 149 | 28 | 59 | 28 | 366 | 28 | 306 | 28 |
| 8 | 90 | 0 | 230 | 43 | 26 | 43 | 340 | 43 | 406 | 43 |
| 9 | 45 | Grain NFOA | 213 | 57 | 38 | 41 | 328 | 43 | 332 | 53 |
| | SED | | 17 | 1 | 11 | 2 | 27 | 0.3 | 21 | 0.6 |
| | $RI_{PLANT\ HEIGHT}$ | | 1.65 | | 1.18 | | 1.02 | | 1.12 | |
| | $RI_{NDVI}$ | | 1.48 | | 1.15 | | 1.06 | | 1.27 | |
| | $RI_{SV}$ | | 1.39 | | 1.52 | | 1.7 | | 1.25 | |
| | $RI_{HARVEST}$ | | 2.99 | | 0.90 | | 1.26 | | 1.68 | |

† NFOA- Nitrogen Fertilizer Optimization Algorithm

‡ Net Return on N Management: assumed (\$0.11 $kg^{-1}$ wheat – Cost of N Management)

§ Cost of N Management assumed: Preplant N of \$0.33 $kg^{-1}$ with \$12.35 $ha^{-1}$ application cost and 2.5% interest on preplant costs. Topdress N assumed \$0.55 $kg^{-1}$ with application costs of \$7.41 $ha^{-1}$. Treatments with variable rates assumed an additional technology fee of \$4.94 $ha^{-1}$

¶ SED- Standard error of the difference between two equally replicated means

# $RI_{PALNT\ HEIGHT}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8 / Plant height of treatment 1)

†† $RI_{NDVI}$ = Response index measured inseason using NDVI readings (NDVI treatment 8 / NDVI treatment 1)

‡‡ $RI_{SV}$ = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED) / (mean NDVI – 1SED))

§§ $RI_{HARVEST}$ = Response index measured using highest grain yield of a preplant N treatment only divided by grain yield of treatment 1

Table 8: Plant height at Feekes 4-6 and response indices at five locations for 2001-2002.

| Location | | | Efaw Upland | Efaw Bottom | Marshall | Hennessey | Kingfisher |
|---|---|---|---|---|---|---|---|
| | Preplant N | Topdress N | Plant Height | Plant Height | Plant Height | Plant Height | Plant Height |
| Trt # | ----------kg ha$^{-1}$-------- | | cm | cm | cm | cm | cm |
| 1 | 0 | 0 | 9.50 | 13.40 | 9.85 | 13.15 | 18.10 |
| 2 | 0 | Forage NFOA | 8.85 | 14.60 | 9.85 | 13.25 | 17.25 |
| 3 | 0 | Grain NFOA | 10.25 | 13.70 | 9.15 | 13.55 | 17.40 |
| 4 | 0 | 2X Grain NFOA | 9.70 | 14.30 | 11.35 | 13.60 | 17.25 |
| 5 | 0 | 45 | 9.30 | 14.45 | 10.35 | 14.35 | 17.80 |
| 6 | 45 | 45 | 9.40 | 15.88 | 11.45 | 14.60 | 18.00 |
| 7 | 45 | 0 | 12.40 | 15.75 | 11.20 | 13.85 | 18.40 |
| 8 | 90 | 0 | 10.95 | 16.15 | 10.10 | 14.15 | 18.25 |
| 9 | 45 | Grain NFOA | 10.70 | 15.50 | 11.10 | 13.90 | 19.00 |
| | | SED | 1.6 | 1.7 | 1.6 | 1.4 | 1.5 |
| | $\mathrm{RI}_{\text{PLANT HEIGHT}}$ | | 1.15 | 1.21 | 1.03 | 1.08 | 1.01 |
| | $\mathrm{RI}_{\text{NDVI}}$ | | 1.27 | 1.06 | 1.11 | 1.23 | 1.01 |
| | $\mathrm{RI}_{\text{SV}}$ | | 1.41 | 1.14 | 1.4 | 1.37 | 1.04 |
| | $\mathrm{RI}_{\text{HARVEST}}$ | | 1.57 | 1.06 | 1.07 | 0.92 | 1.06 |

† $\mathrm{RI}_{\text{PALNT HEIGHT}}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8 / Plant height of treatment 1)

‡ $\mathrm{RI}_{\text{NDVI}}$ = Response index measured in-season using NDVI readings (NDVI treatment 8 / NDVI treatment 1)

§ $\mathrm{RI}_{\text{SV}}$ = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED) / (mean NDVI – 1SED))

¶ $\mathrm{RI}_{\text{HARVEST}}$ = Response index measured using highest grain yield of a preplant N treatment only divided by grain yield of treatment 1

# SED- Standard error of the difference between two equally replicated means

†† NFOA- Nitrogen Fertilizer Optimization Algorithm

Table 9: Plant heights at Feekes 4-6 and response indices at four locations for 2002-2003.

| Location | | | Efaw Upland | Tipton | Perkins | Lake Carl Blackwell |
|---|---|---|---|---|---|---|
| | Preplant N | Topdress N | Plant Height | Plant Height | Plant Height | Plant Height |
| Trt # | ---------kg ha$^{-1}$--------- | | cm | cm | cm | cm |
| 1 | 0 | 0 | 6.20 | 14.95 | 15.90 | 12.25 |
| 2 | 0 | Forage NFOA | 6.20 | 16.10 | 15.90 | 12.10 |
| 3 | 0 | Grain NFOA | 6.05 | 15.7 | 15.95 | 12.40 |
| 4 | 0 | 2X Grain NFOA | 6.50 | 15.3 | 15.30 | 11.65 |
| 5 | 0 | 45 | 7.35 | 14.75 | 14.95 | 12.85 |
| 6 | 45 | 45 | 9.10 | 16.75 | 16.50 | 12.80 |
| 7 | 45 | 0 | 8.90 | 16.00 | 16.10 | 12.55 |
| 8 | 90 | 0 | 10.20 | 17.65 | 16.25 | 13.70 |
| 9 | 45 | Grain NFOA | 8.60 | 15.9 | 15.90 | 13.05 |
| | | SED | 1.11 | 1.3 | 1.25 | 1.0 |
| | $\mathrm{RI}_{\mathrm{PLANT\ HEIGHT}}$ | | 1.65 | 1.18 | 1.02 | 1.12 |
| | $\mathrm{RI}_{\mathrm{NDVI}}$ | | 1.48 | 1.15 | 1.06 | 1.27 |
| | $\mathrm{RI}_{\mathrm{SV}}$ | | 1.39 | 1.52 | 1.7 | 1.25 |
| | $\mathrm{RI}_{\mathrm{HARVEST}}$ | | 2.99 | 0.90 | 1.26 | 1.68 |

† $\mathrm{RI}_{\mathrm{PALNT\ HEIGHT}}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8 / Plant height of treatment 1)
‡ $\mathrm{RI}_{\mathrm{NDVI}}$ = Response index measured in-season using NDVI readings (NDVI treatment 8 / NDVI treatment 1)
§ $\mathrm{RI}_{\mathrm{SV}}$ = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED) / (mean NDVI – 1SED))
¶ $\mathrm{RI}_{\mathrm{HARVEST}}$ = Response index measured using highest grain yield of a preplant N treatment only divided by grain yield of treatment 1
# SED- Standard error of the difference between two equally replicated means
†† NFOA- Nitrogen Fertilizer Optimization Algorithm

Table 10: Averages across all nine locations and two years.

| | Preplant N | Topdress N | Grain Yield | NUE | Net Ret. | Cost | Grain N |
|---|---|---|---|---|---|---|---|
| Trt # | ---------kg ha$^{-1}$ | ------- | kg ha$^{-1}$ | % | \$ ha$^{-1}$ | \$ ha$^{-1}$ | N g kg$^{-1}$ |
| 1 | 0 | 0 | 2002 | | 220 | 0 | 21.4 |
| 2 | 0 | Forage NFOA | 2328 (30) | 31 | 227 | 30 | 22.1 |
| 3 | 0 | Grain NFOA | 2073 (10) | 68 | 211 | 18 | 21.0 |
| 4 | 0 | 2X Grain NFOA | 2813 (72) | 25 | 258 | 52 | 23.4 |
| 5 | 0 | 45 | 2473 | 24 | 240 | 32 | 21.9 |
| 6 | 45 | 45 | 2874 | 20 | 256 | 60 | 22.4 |
| 7 | 45 | 0 | 2363 | 20 | 232 | 28 | 21.7 |
| 8 | 90 | 0 | 2608 | 14 | 244 | 43 | 22.2 |
| 9 | 45 | Grain NFOA | 2499 (11) | 18 | 229 | 46 | 22.1 |
| | | SED | 272 | 35 | 29 | 4.12 | 1.21 |

† Numbers in parentheses indicates the average amount of topdress N applied for variable rate treatments

‡ Net Return on N Management: assumed (\$0.11 kg$^{-1}$ wheat – Cost of N Management)

§ Cost of N Management assumed: Preplant N of \$0.33 kg$^{-1}$ with \$12.35 ha$^{-1}$ application cost and 2.5% interest on preplant costs. Topdress N assumed \$0.55 kg$^{-1}$ with application costs of \$7.41 ha$^{-1}$. Treatments with variable rates assumed an additional technology fee of \$4.94 ha$^{-1}$

¶ NUE is calculated as: (Grain N uptake of N treatment) – (Grain N uptake of check)) / (Total amount of N applied).

\# SED- Standard error of the difference between two equally replicated means

†† $RI_{PALNT\ HEIGHT}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8 / Plant height of treatment 1)

‡‡ $RI_{NDVI}$ = Response index measured inseason using NDVI readings (NDVI treatment 8 / NDVI treatment 1)

§§ $RI_{SV}$ = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED) / (mean NDVI – 1SED))

¶¶ $RI_{HARVEST}$ = Response index measured using highest grain yield of a preplant N treatment only divided by grain yield of treatment 1

\## NFOA- Nitrogen Fertilizer Optimization Algorithm

Table 11: Grain N and harvest index at five sites for 2001-2002.

| Location | | | Efaw Upland | Efaw Bottom | Marshall | Hennessey | Kingfisher |
|---|---|---|---|---|---|---|---|
| | Preplant N | Topdress N | Grain N | Grain N | Grain N | Grain N | Grain N |
| Trt # | ----------kg ha$^{-1}$-------- | | g kg$^{-1}$ | g kg$^{-1}$ | g kg$^{-1}$ | g kg$^{-1}$ | g kg$^{-1}$ |
| 1 | 0 | 0 | 17 | 21 | 22 | 25 | 29 |
| 2 | 0 | Forage NFOA | 19 | 21 | 20 | 23 | 30 |
| 3 | 0 | Grain NFOA | 19 | 21 | 21 | 22 | 28 |
| 4 | 0 | 2X Grain NFOA | 21 | 21 | 21 | 24 | 32 |
| 5 | 0 | 45 | 20 | 22 | 22 | 23 | 31 |
| 6 | 45 | 45 | 18 | 20 | 23 | 25 | 31 |
| 7 | 45 | 0 | 17 | 21 | 22 | 23 | 31 |
| 8 | 90 | 0 | 18 | 23 | 22 | 24 | 31 |
| 9 | 45 | Grain NFOA | 18 | 23 | 22 | 25 | 31 |
| | | SED | 1 | 1 | 1 | 2 | 1 |
| | $RI_{PLANT\ HEIGHT}$ | | 1.15 | 1.21 | 1.03 | 1.08 | 1.01 |
| | $RI_{NDVI}$ | | 1.27 | 1.06 | 1.11 | 1.23 | 1.01 |
| | $RI_{SV}$ | | 1.41 | 1.14 | 1.4 | 1.37 | 1.04 |
| | $RI_{HARVEST}$ | | 1.57 | 1.06 | 1.07 | 0.92 | 1.06 |

† $RI_{PALNT\ HEIGHT}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8 / Plant height of treatment 1)

‡ $RI_{NDVI}$ = Response index measured in-season using NDVI readings (NDVI treatment 8 / NDVI treatment 1)

§ $RI_{SV}$ = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED) / (mean NDVI – 1SED))

¶ $RI_{HARVEST}$ = Response index measured using highest grain yield of a preplant N treatment only divided by grain yield of treatment 1

\# SED- Standard error of the difference between two equally replicated means

†† NFOA- Nitrogen Fertilizer Optimization Algorithm

Table 12: Grain N and harvest index at four sites for 2002-2003.

| Location | | | Efaw Upland | Tipton | Perkins | Lake Carl Blackwell |
|---|---|---|---|---|---|---|
| | Preplant N | Topdress N | Grain N | Grain N | Grain N | Grain N |
| Trt # | ----------kg ha$^{-1}$---------- | | g kg$^{-1}$ | g kg$^{-1}$ | g kg$^{-1}$ | g kg$^{-1}$ |
| 1 | 0 | 0 | 20 | 22 | 21 | 17 |
| 2 | 0 | Forage NFOA | 19 | 25 | 23 | 18 |
| 3 | 0 | Grain NFOA | 20 | 22 | 21 | 15 |
| 4 | 0 | 2X Grain NFOA | 23 | 25 | 24 | 20 |
| 5 | 0 | 45 | 19 | 24 | 23 | 17 |
| 6 | 45 | 45 | 19 | 25 | 24 | 17 |
| 7 | 45 | 0 | 18 | 23 | 23 | 17 |
| 8 | 90 | 0 | 18 | 22 | 23 | 18 |
| 9 | 45 | Grain NFOA | 19 | 22 | 21 | 17 |
| | | SED | 1 | 1 | 1 | 1 |
| | RI$_{\text{PLANT HEIGHT}}$ | | 1.65 | 1.18 | 1.02 | 1.12 |
| | RI$_{\text{NDVI}}$ | | 1.48 | 1.15 | 1.06 | 1.27 |
| | RI$_{\text{SV}}$ | | 1.39 | 1.52 | 1.7 | 1.25 |
| | RI$_{\text{HARVEST}}$ | | 2.99 | 0.90 | 1.26 | 1.68 |

† RI$_{\text{PALNT HEIGHT}}$ = Response index measured in-season using mean canopy height (Plant height of treatment 8 / Plant height of treatment 1)

‡ RI$_{\text{NDVI}}$ = Response index measured in-season using NDVI readings (NDVI treatment 8 / NDVI treatment 1)

§ RI$_{\text{SV}}$ = Response index measured in-season using NDVI readings of treatments 1 thru 5 ((mean NDVI + 1 SED) / (mean NDVI – 1SED))

¶ RI$_{\text{HARVEST}}$ = Response index measured using highest grain yield of a preplant N treatment only divided by grain yield of treatment 1

# SED- Standard error of the difference between two equally replicated means

†† NFOA- Nitrogen Fertilizer Optimization Algorithm

Figure 1: $RI_{NDVI}$ at Feekes 4-6 versus $RI_{HARVEST}$ at nine sites for 2001-2003 crop years

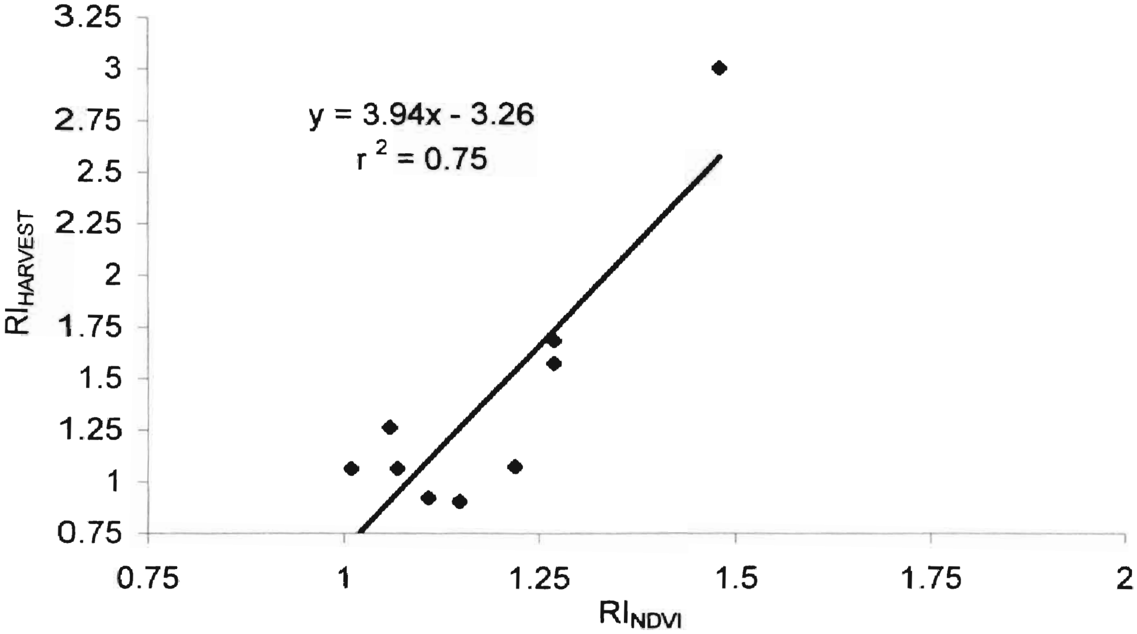


Figure 2: $RI_{Plantheight}$ at Feekes 4-6 versus $RI_{HARVEST}$ at nine sites for 2001-2003 crop years

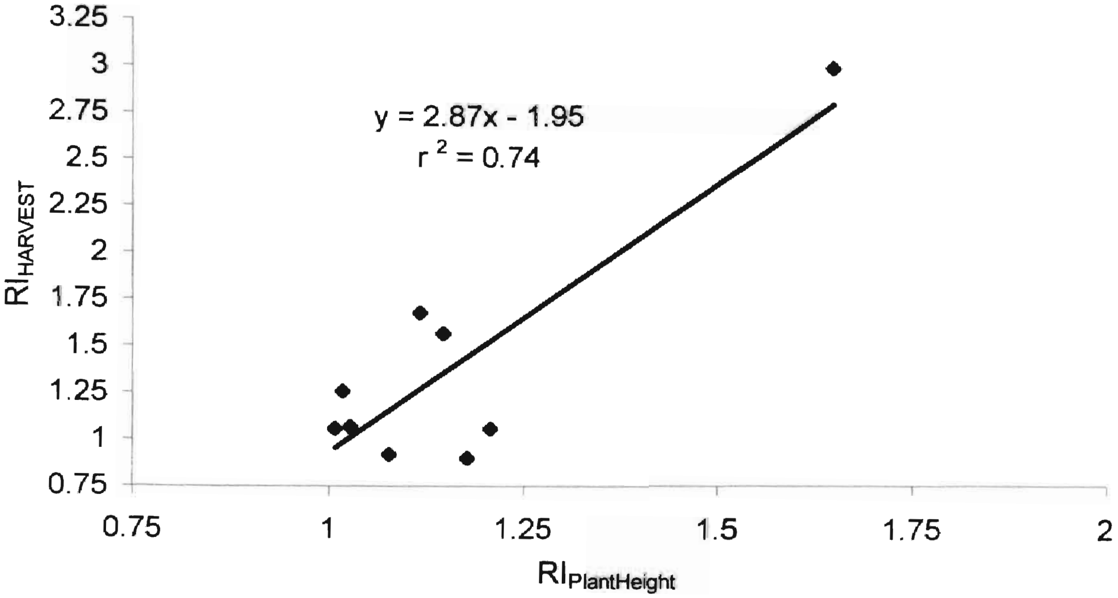


Figure 3: $RI_{Plantheight}$ at Feekes 4-6 versus $RI_{NDVI}$ at nine sites for 2001-2003 crop years.

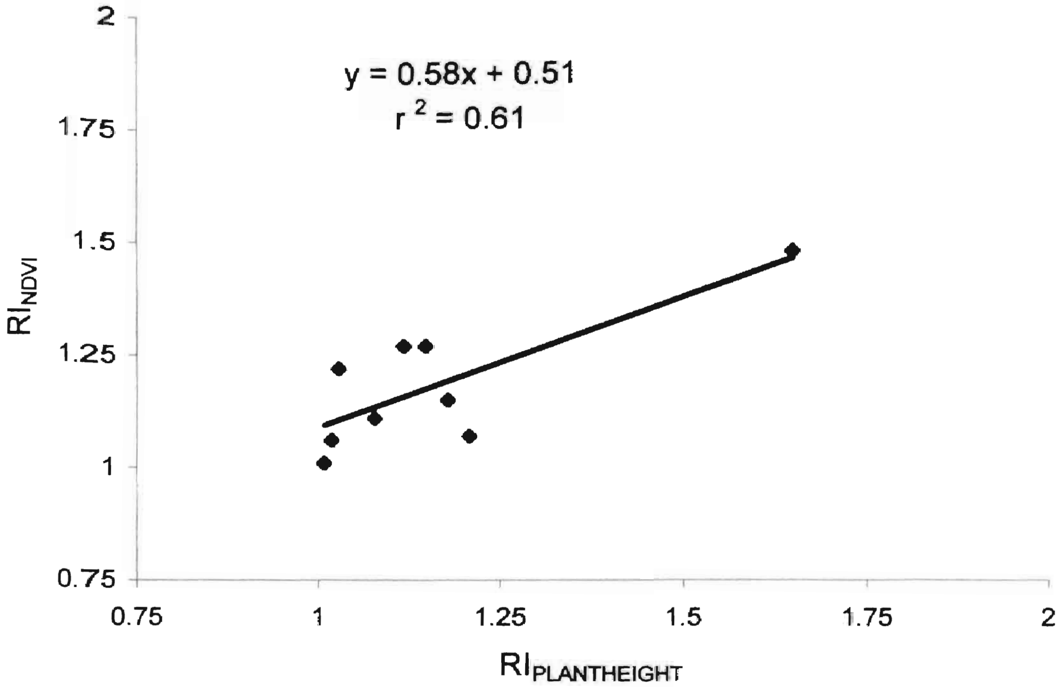


Figure 4: $RI_{SV}$ at Feekes 4-6 versus $RI_{HARVEST}$ at nine sites for 2001-2003 crop years

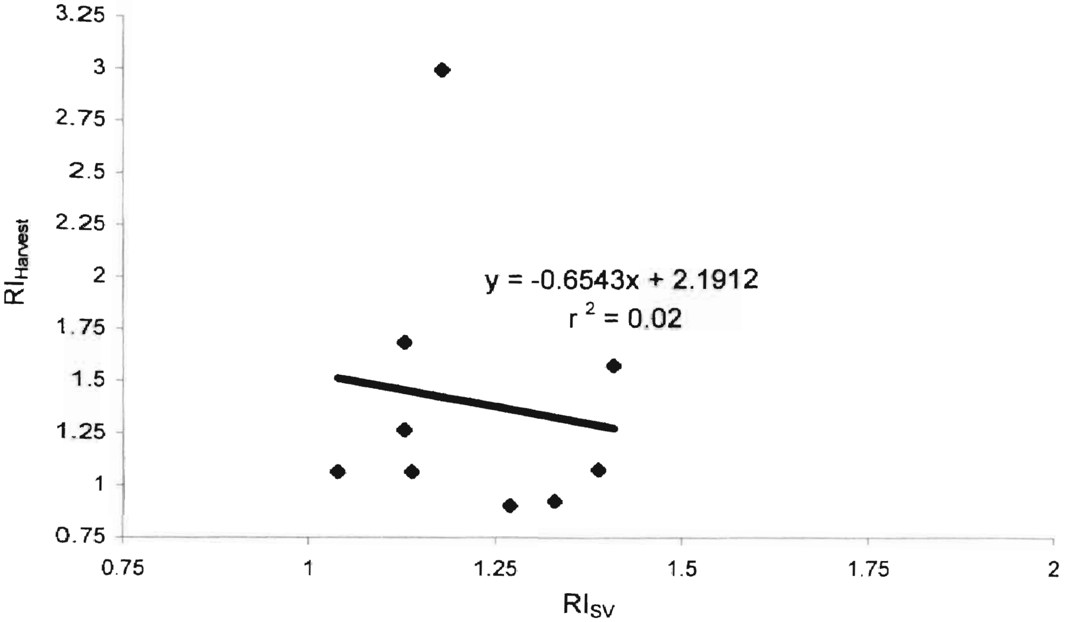


Figure 5: $RI_{SV}$ at Feekes 4-6 versus $RI_{NDVI}$ at nine sites for 2001-2003 crop years

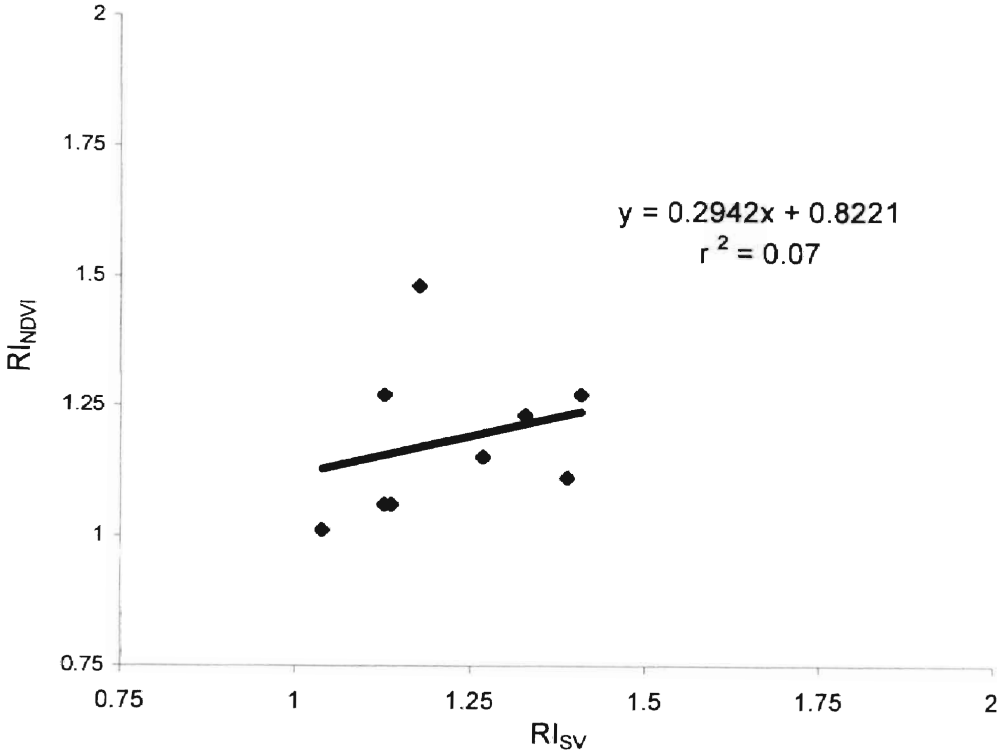
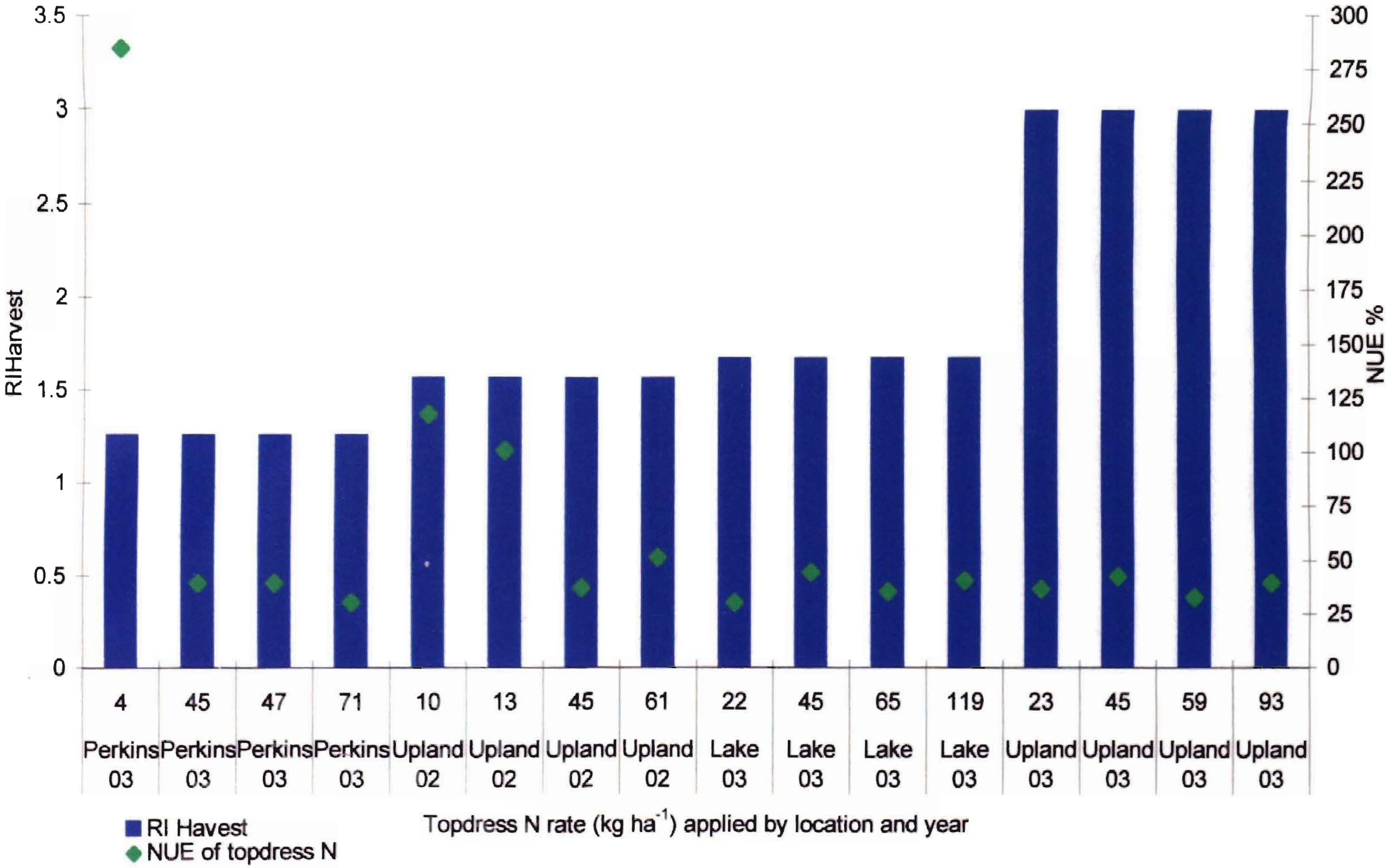
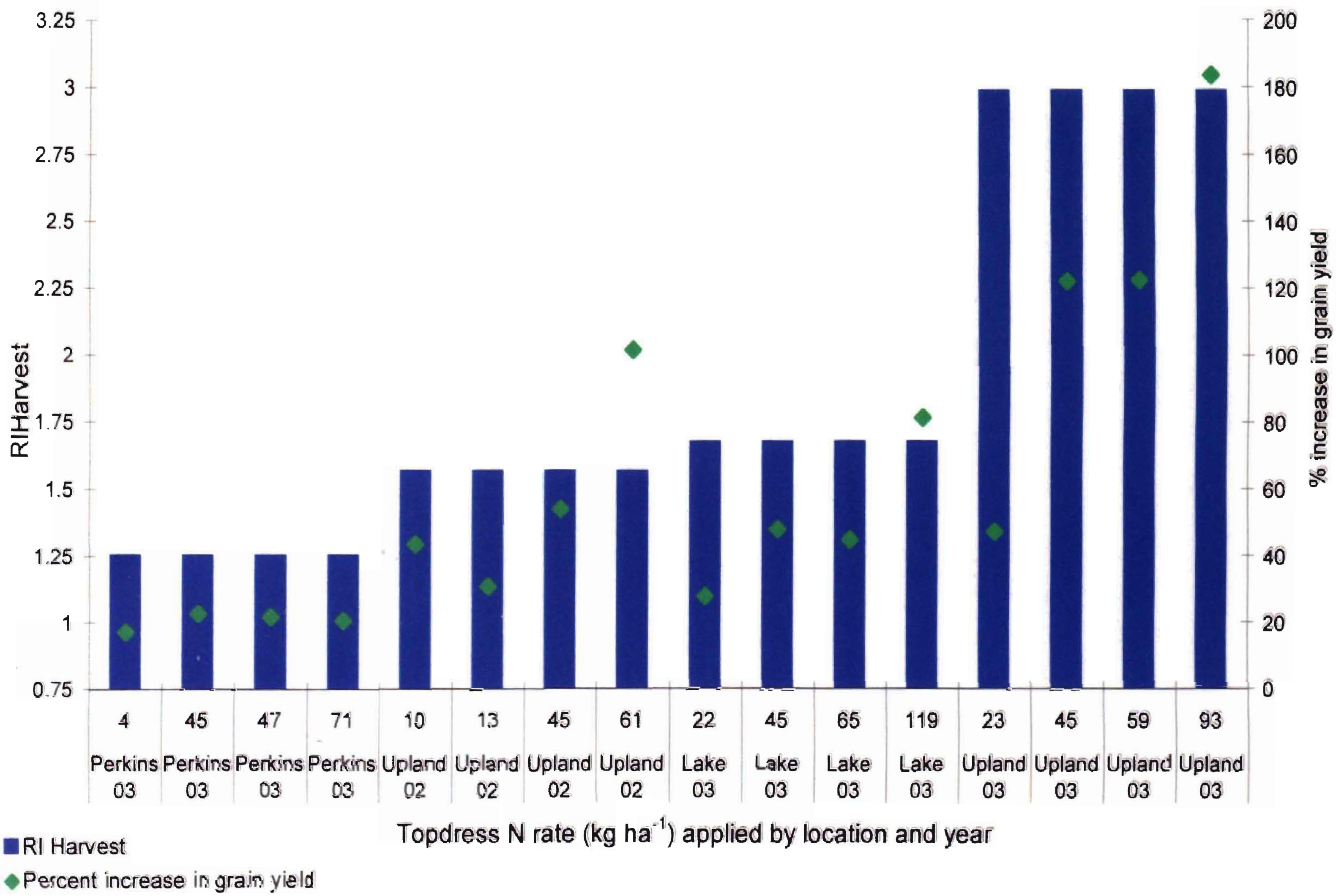


Figure 6: NUE of topdress N rates by $RI_{Harvest}$ at four N responsive sites for 2001-2003 crop years.



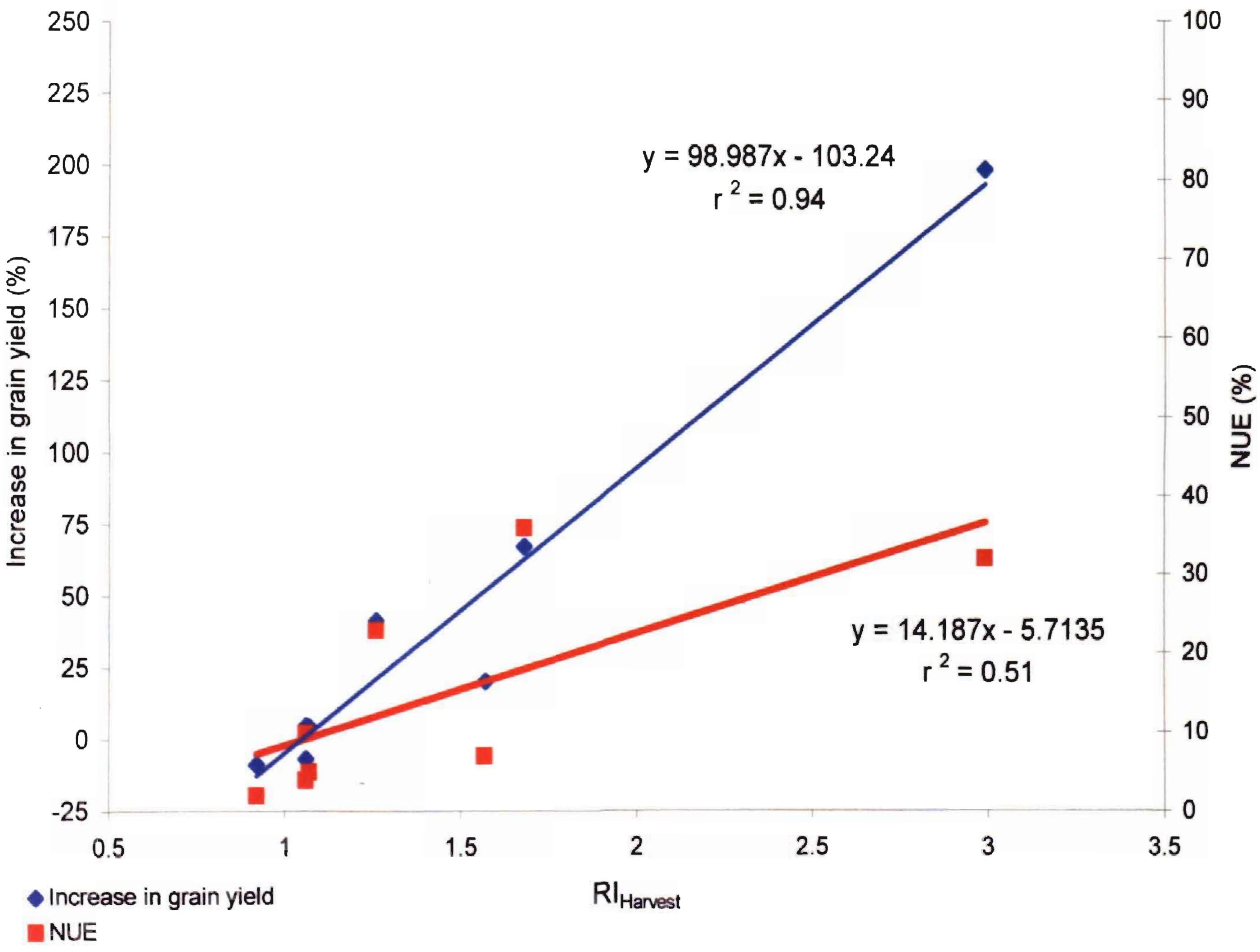
† Tipton site was omitted due to a late freeze occurring over a month after topdress N application.

Figure 7: Percent increase in grain yield of topdress N rates by $RI_{Harvest}$ at four N responsive sites for. 2001-2003 crop years



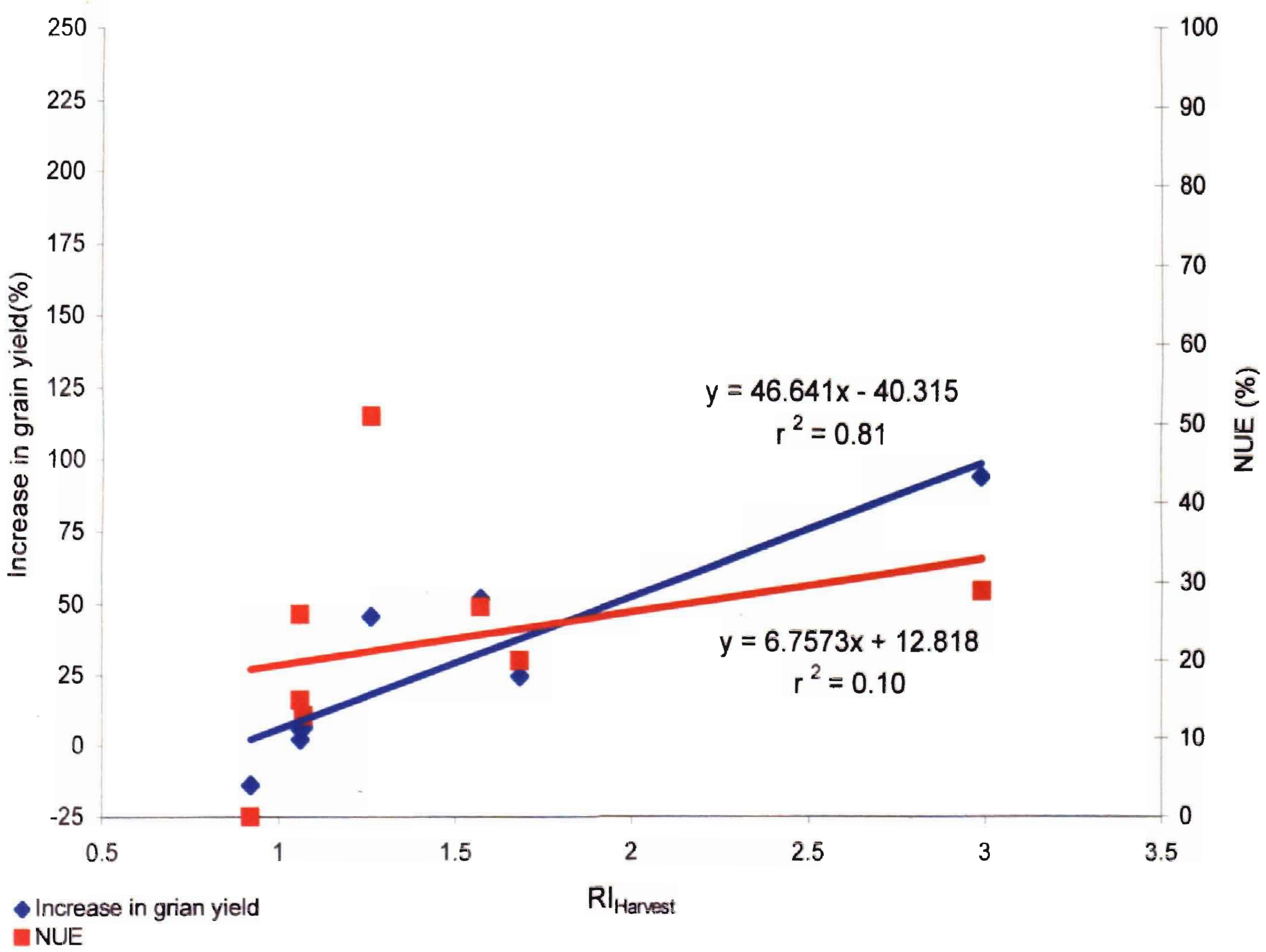
† Tipton site was omitted due to a late freeze occurring over a month after topdress N application.

Figure 8: Relationship of winter wheat grain yield and nitrogen use efficiency to response index when 90 kg ha$^{-1}$ is applied preplant (2001-2003).



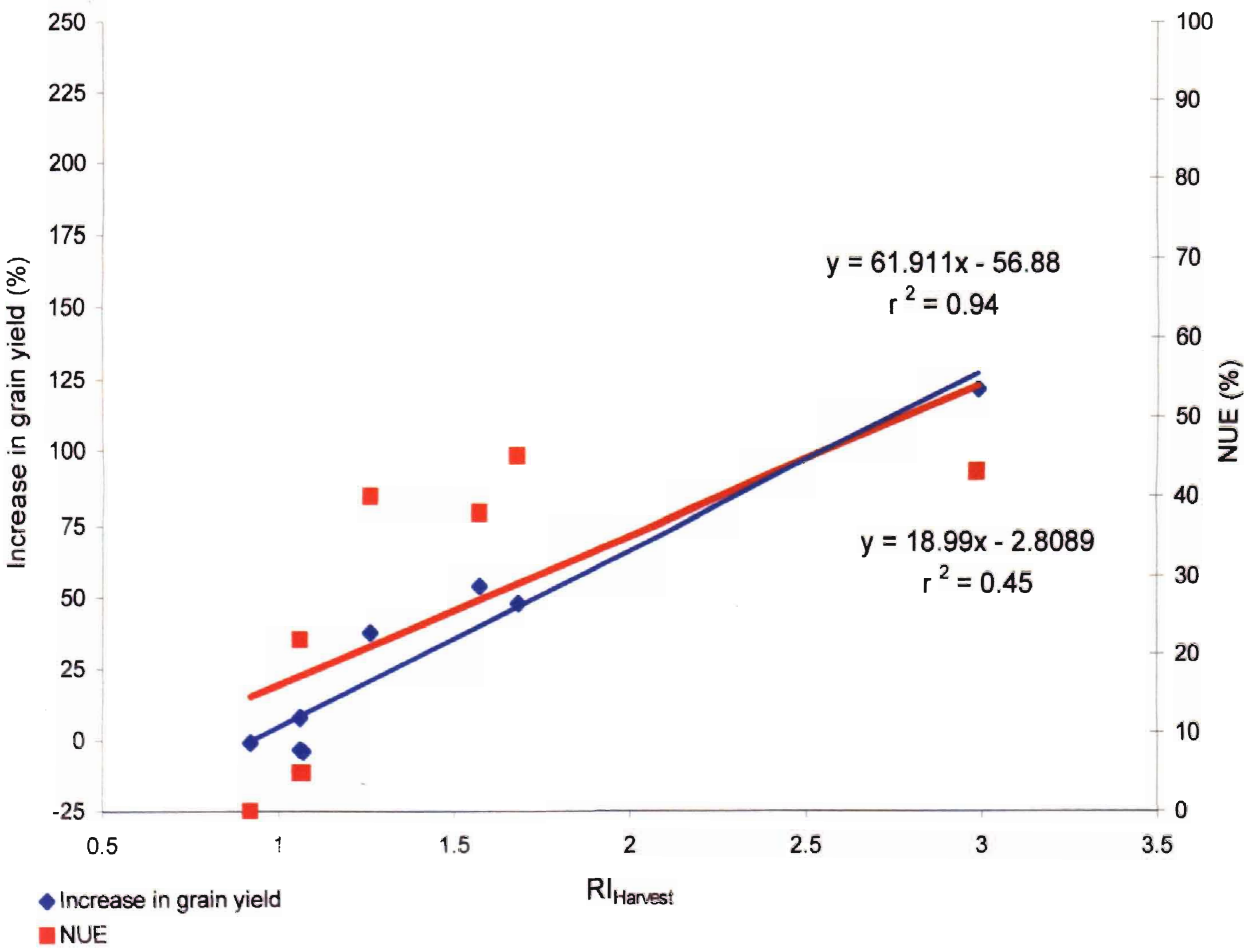
† Tipton site was omitted due to a late freeze occurring over a month after topdress N application.

Figure 9: Relationship of winter wheat grain yield and nitrogen use efficiency to response index when 45 kg ha$^{-1}$ is applied preplant (2001-2003).



† Tipton site was omitted due to a late freeze occurring over a month after topdress N application.

Figure 10: Relationship of winter wheat grain yield and nitrogen use efficiency to response index when 45 kg $ha^{-1}$ is applied topdress (2001-2003).



† Tipton site was omitted due to a late freeze occurring over a month after topdress N application.

# APPENDIXES

## Appendix A

Analysis of variance of four non-N-responsive sites 2001-2002.

| Location: | | Efaw Bottom | | | | |
|---|---|---|---|---|---|---|
| | | Grain Yield kg ha$^{-1}$ | Ret. On N Mgt. \$ ha$^{-1}$ | Cost of N Mgt. \$ ha$^{-1}$ | Grain N g kg$^{-1}$ | Harvest Index % |
| Source of variation | df | Mean squares | | | | |
| Replication | 3 | 412265** | 4780** | 6.27 | 28 ** | 16 |
| N Treatment | 8 | 177863* | 1595 | 1181.25** | 3 | 14 |
| Residual error | 18 | 59215 | 685 | 5.64 | 2 | 14 |
| | SED | 172 | 19 | 2 | 1.0 | 3 |

| Location: | | Marshall | | | | |
|---|---|---|---|---|---|---|
| | | Grain Yield kg ha$^{-1}$ | Ret. On N Mgt. \$ ha$^{-1}$ | Cost of N Mgt. \$ ha$^{-1}$ | Grain N g kg$^{-1}$ | Harvest Index g kg$^{-1}$ |
| Source of variation | df | Mean squares | | | | |
| Replication | 3 | 344958 | 3944 | 3.27 | 14** | 747 |
| N Treatment | 8 | 310892 | 2833 | 912.32** | 2 | 1363* |
| Residual error | 15 | 139395 | 1646 | 3.95 | 1 | 461 |
| | SED | 264 | 29 | 1 | 1 | 15 |

| Location: | | Hennessey | | | | |
|---|---|---|---|---|---|---|
| | | Grain Yield kg ha$^{-1}$ | Ret. On N Mgt. \$ ha$^{-1}$ | Cost of N Mgt. \$ ha$^{-1}$ | Grain N g kg$^{-1}$ | Harvest Index g kg$^{-1}$ |
| Source of variation | df | Mean squares | | | | |
| Replication | 3 | 80104 | 892 | 0.98 | 8 | 8 |
| N Treatment | 8 | 198256* | 2000* | 123.06** | 5 | 11 |
| Residual error | 19 | 59972 | 728 | 9.11 | 5 | 6 |
| | SED | 173 | 19 | 2 | 2 | 2 |

| Location: | | Kingfisher | | | | |
|---|---|---|---|---|---|---|
| | | Grain Yield kg ha$^{-1}$ | Ret. On N Mgt. \$ ha$^{-1}$ | Cost of N Mgt. \$ ha$^{-1}$ | Grain N g kg$^{-1}$ | Harvest Index g kg$^{-1}$ |
| Source of variation | df | Mean squares | | | | |
| Replication | 3 | 65716 | 756 | 1.44 | 12** | 82** |
| N Treatment | 8 | 237953* | 3385* | 1388.97** | 4* | 19 |
| Residual error | 20 | 88769 | 1090 | 1.69 | 1 | 17 |
| | SED | 211 | 23 | 1 | 1 | 3 |

* Significant at the 0.05 probability level,
** Significant at the 0.01 probability level,

† SED- Standard error of the difference between two equally replicated means

## Appendix B

Analysis of variance of one N responsive site 2001-2002.

| Location: | | Efaw Upland | | | | |
|---|---|---|---|---|---|---|
| | | Grain Yield kg ha$^{-1}$ | Ret. On N Mgt. \$ ha$^{-1}$ | Cost of N Mgt. \$ ha$^{-1}$ | Grain N g kg$^{-1}$ | Harvest Index % |
| | | Mean squares | | | | |
| Source of variation | df | | | | | |
| Replication | 3 | 38301 | 406 | 34.86 | 1 | 114 |
| N Treatment | 8 | 631587** | 4023* | 1218.16** | 4 | 72 |
| Residual error | 19 | 119756 | 1387 | 20.75 | 3 | 53 |
| | SED | 245 | 26 | 3 | 1 | 5 |

* Significant at the 0.05 probability level,

** Significant at the 0.01 probability level,

† SED- Standard error of the difference between two equally replicated means

## Appendix C

Analysis of variance of four sites for 2002-2003.

| Location: | | Efaw Upland | | | | |
|---|---|---|---|---|---|---|
| | | Grain Yield kg ha$^{-1}$ | Ret. On N Mgt. \$ ha$^{-1}$ | Cost of N Mgt. \$ ha$^{-1}$ | Grain N g kg$^{-1}$ | Harvest Index g kg$^{-1}$ |
| Source of variation | df | Mean squares | | | | |
| Replication | 3 | 217687* | 2686* | 6.08 | 7** | 15 |
| N Treatment | 8 | 1535000** | 10186** | 1551.35** | 7** | 64 |
| Residual error | 21 | 49744 | 580 | 3.79 | 1 | 55 |
| | SED | 158 | 17 | 1 | 1 | 5 |

| Location: | | Tipton | | | | |
|---|---|---|---|---|---|---|
| | | Grain Yield kg ha$^{-1}$ | Ret. On N Mgt. \$ ha$^{-1}$ | Cost of N Mgt. \$ ha$^{-1}$ | Grain N g kg$^{-1}$ | Harvest Index g kg$^{-1}$ |
| Source of variation | df | Mean squares | | | | |
| Replication | 3 | 48976 | 637 | 5.50 | 1 | 81** |
| N Treatment | 8 | 162393** | 964** | 1206.02** | 6** | 24* |
| Residual error | 20 | 21017 | 229 | 4.61 | 1 | 8 |
| | SED | 103 | 11 | 2 | 1 | 2 |

| Location: | | Perkins | | | | |
|---|---|---|---|---|---|---|
| | | Grain Yield kg ha$^{-1}$ | Ret. On N Mgt. \$ ha$^{-1}$ | Cost of N Mgt. \$ ha$^{-1}$ | Grain N g kg$^{-1}$ | Harvest Index g kg$^{-1}$ |
| Source of variation | df | Mean squares | | | | |
| Replication | 3 | 38813 | 463 | 0.19 | 6* | 65 |
| N Treatment | 8 | 206273 | 967 | 1169.96 | 4 | 19 |
| Residual error | 19 | 117067 | 1425 | 0.17 | 2 | 43 |
| | SED | 242 | 27 | 0.3 | 1 | 5 |

| Location: | | Lake Carl Blackwell | | | | |
|---|---|---|---|---|---|---|
| | | Grain Yield kg ha$^{-1}$ | Ret. On N Mgt. \$ ha$^{-1}$ | Cost of N Mgt. \$ ha$^{-1}$ | Grain N g kg$^{-1}$ | Harvest Index g kg$^{-1}$ |
| Source of variation | df | Mean squares | | | | |
| Replication | 3 | 79009 | 975 | 0.59 | 0.3 | 10 |
| N Treatment | 8 | 1275080** | 7837** | 1726.05 | 6** | 35* |
| Residual error | 18 | 72177 | 862 | 0.73 | 1 | 10 |
| | SED | 190 | 21 | 0.60 | 1 | 2 |

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

† SED- Standard error of the difference between two equally replicated means

## Appendix D

Analysis of variance of NUE at five sites 2001-2002.

| **Location:** | | **Efaw bottom** |
|---|---|---|
| | | NUE |
| | | % |
| Source of variation | df | Mean squares |
| Replication | 3 | 1478* |
| N Treatment | 7 | 960* |
| Residual error | 16 | 313 |
| | SED | 13 |

| **Location:** | | Marshall |
|---|---|---|
| | | NUE |
| | | % |
| Source of variation | df | Mean squares |
| Replication | 3 | 4677 |
| N Treatment | 7 | 1970 |
| Residual error | 14 | 2097 |
| | SED | 33 |

| Location: | | Hennessey |
|---|---|---|
| | | NUE |
| | | % |
| Source of variation | df | Mean squares |
| Replication | 3 | 27 |
| N Treatment | 7 | 84* |
| Residual error | 17 | 33 |
| | SED | 4 |

| Location: | | Kingfisher |
|---|---|---|
| | | NUE |
| | | % |
| Source of variation | df | Mean squares |
| Replication | 3 | 106 |
| N Treatment | 7 | 244 |
| Residual error | 17 | 141 |
| | SED | 8 |

| Location: | | Efaw Upland |
|---|---|---|
| | | NUE |
| Source of variation | df | Mean squares |
| Replication | 3 | 1591 |
| N Treatment | 7 | 4662* |
| Residual error | 15 | 1183 |
| | SED | 24 |

* Significant at the 0.05 probability level,
** Significant at the 0.01 probability level,
† SED- Standard error of the difference between two equally replicated means

# Appendix E

Analysis of variance of NUE at four sites for 2002-2003.

| Location: | | Efaw Upland |
|---|---|---|
| | | NUE |
| Source of variation | df | Mean squares |
| Replication | 3 | 108 |
| N Treatment | 7 | 102 |
| Residual error | 18 | 94 |
| | SED | 7 |

| Location: | | Tipton |
|---|---|---|
| | | NUE |
| Source of variation | df | Mean squares |
| Replication | 3 | 298 |
| N Treatment | 7 | 156 |
| Residual error | 17 | 103 |
| | SED | 7 |

| Location: | | Perkins |
|---|---|---|
| | | NUE |
| Source of variation | df | Mean squares |
| Replication | 3 | 11685 |
| N Treatment | 7 | 28573* |
| Residual error | 17 | 9326 |
| | SED | 68 |

| Location: | | Lake Carl Blackwell |
|---|---|---|
| | | NUE |
| Source of variation | df | Mean squares |
| Replication | 3 | 37 |
| N Treatment | 7 | 193 |
| Residual error | 15 | 113 |
| | SED | 8 |

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

† SED- Standard error of the difference between two equally replicated means

# Appendix F

Analysis of variance for 2001-2002 plant height of five sites.

| Location: | Efaw Bottom | |
|---|---|---|
| | | Plant Height cm |
| Source of variation | df | Mean Squares |
| Replication | 3 | 80.15** |
| N Treatment | 8 | 19.81** |
| Residual error | 168 | 5.83 |
| | SED | 1.7 |

| Location: | Marshall | |
|---|---|---|
| | | Plant Height Cm |
| Source of variation | df | Mean Squares |
| Replication | 3 | 18.56* |
| N Treatment | 8 | 13.31* |
| Residual error | 168 | 5.43 |
| | SED | 1.6 |

| Location: | Hennessey | |
|---|---|---|
| | | Plant Height Cm |
| Source of variation | df | Mean Squares |
| Replication | 3 | 9.23 |
| N Treatment | 8 | 4.75 |
| Residual error | 168 | 3.94 |
| | SED | 1.4 |

| Location: | Kingfisher | |
|---|---|---|
| | | Plant Height Cm |
| Source of variation | df | Mean Squares |
| Replication | 3 | 65.35** |
| N Treatment | 8 | 6.81 |
| Residual error | 168 | 4.65 |
| | SED | 1.5 |

| Location: | Efaw Upland | |
|---|---|---|
| | | Plant Height Cm |
| Source of variation | df | Mean Squares |
| Replication | 3 | 83.26** |
| N Treatment | 8 | 24.01** |
| Residual error | 168 | 5.00 |
| | SED | 1.6 |

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

† SED- Standard error of the difference between two equally replicated means

Appendix G

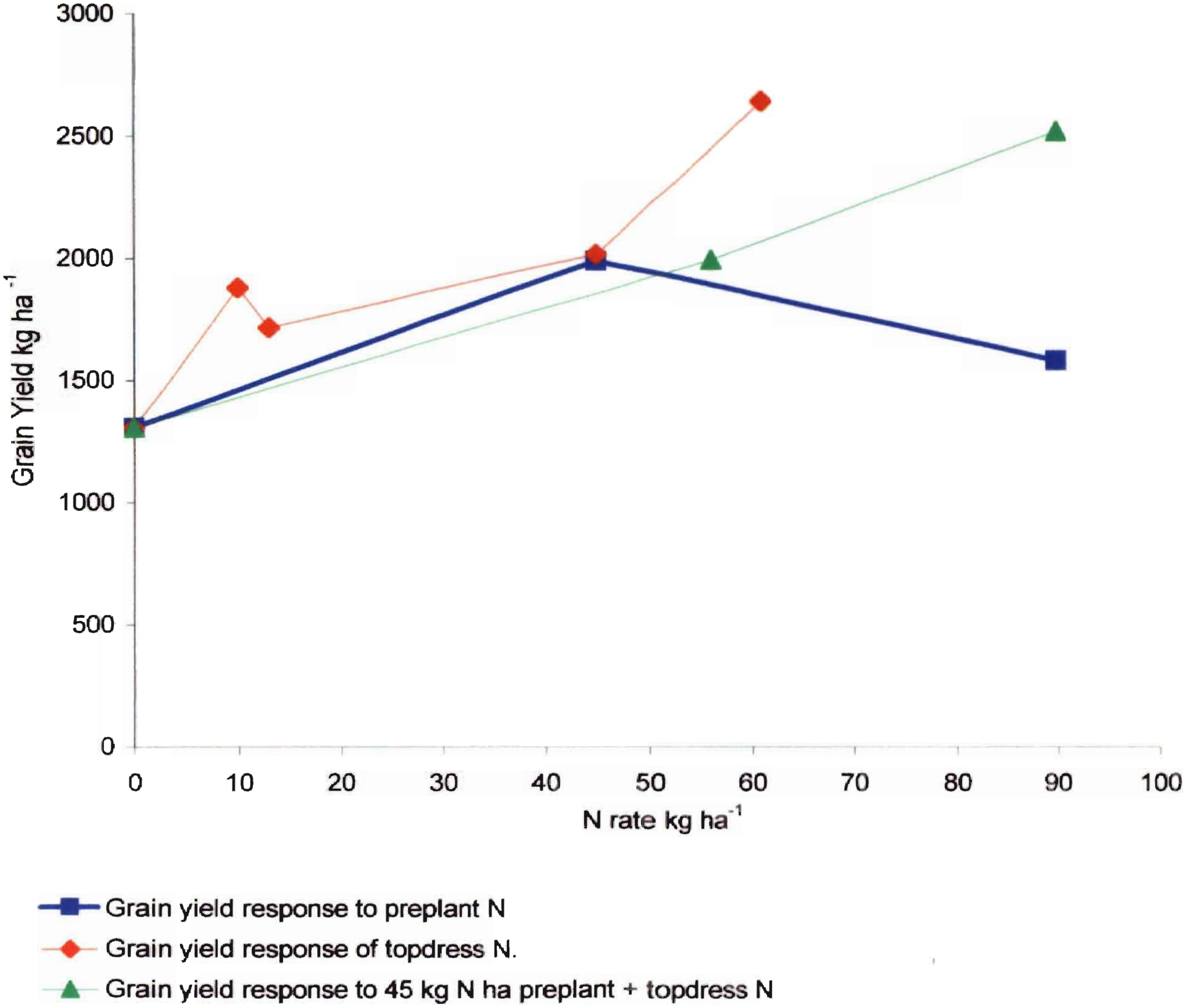
Analysis of variance for 2002-2003 plant height of four sites.

| Location: | | Efaw Upland |
|---|---|---|
| | | Plant Height cm |
| Source of variation | df | Mean Squares |
| Replication | 3 | 29.41** |
| N Treatment | 8 | 48.10** |
| Residual error | 168 | 2.48 |
| | SED | 1.11 |
| Location: | | Tipton |
| | | Plant Height Cm |
| Source of variation | df | Mean Squares |
| Replication | 3 | 4.07 |
| N Treatment | 8 | 16.15** |
| Residual error | 24 | 3.36 |
| | SED | 1.30 |
| Location: | | Perkins |
| | | Plant Height Cm |
| Source of variation | df | Mean Squares |
| Replication | 3 | 7.07 |
| N Treatment | 8 | 4.43 |
| Residual error | 168 | 3.11 |
| | SED | 1.25 |
| Location: | | Lake Carl Blackwell |
| | | Plant Height Cm |
| Source of variation | df | Mean Squares |
| Replication | 3 | 7.87** |
| N Treatment | 8 | 7.08** |
| Residual error | 24 | 1.51 |
| | SED | 1.0 |

* Significant at the 0.05 probability level
** Significant at the 0.01 probability level
† SED- Standard error of the difference between two equally replicate

## Appendix H

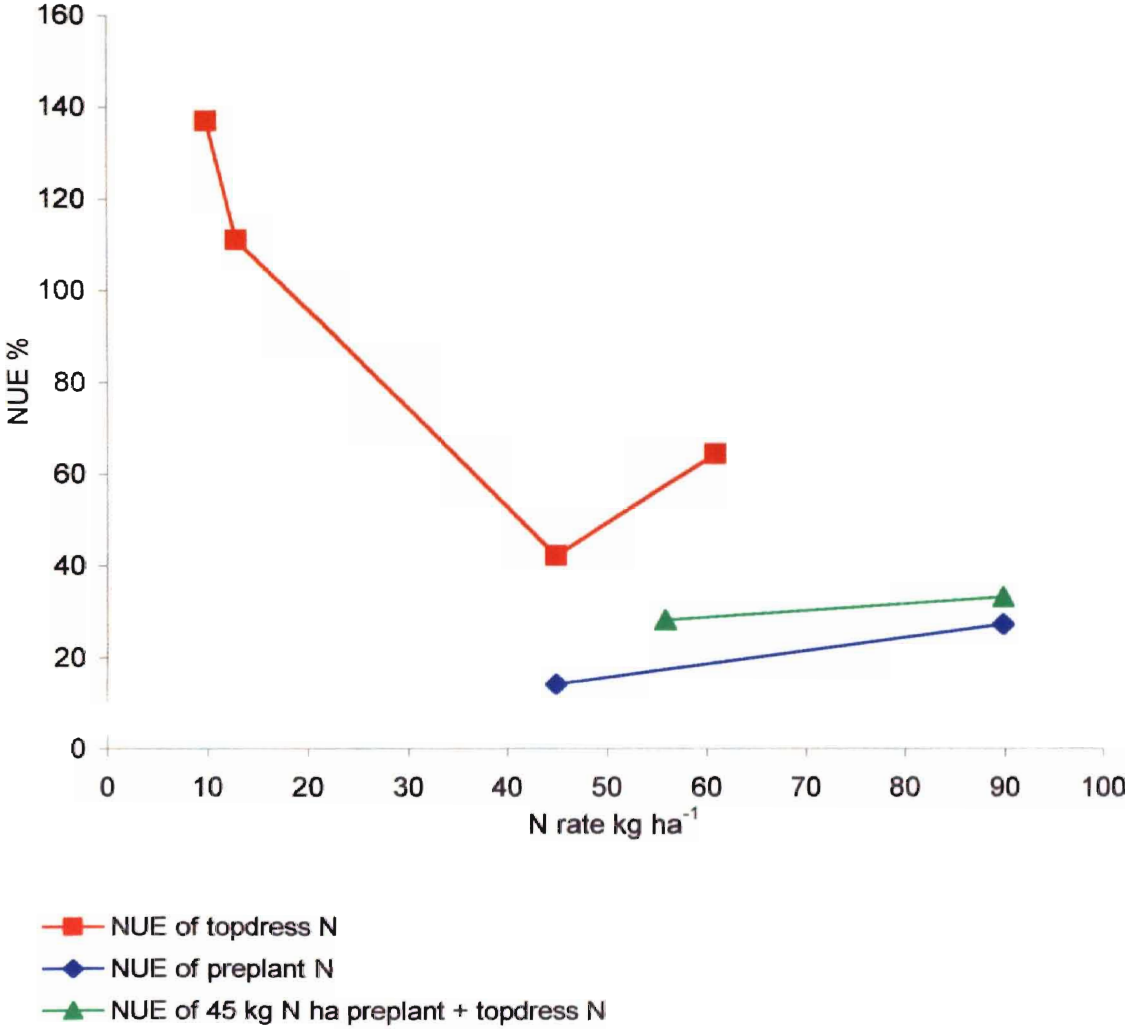
Grain yield of preplant, topdress and split application N rates at Efaw Upland 2001-2002.



† $RI_{NDVI}$ = 1.27
‡ $RI_{Harvest}$ = 1.57

## Appendix I

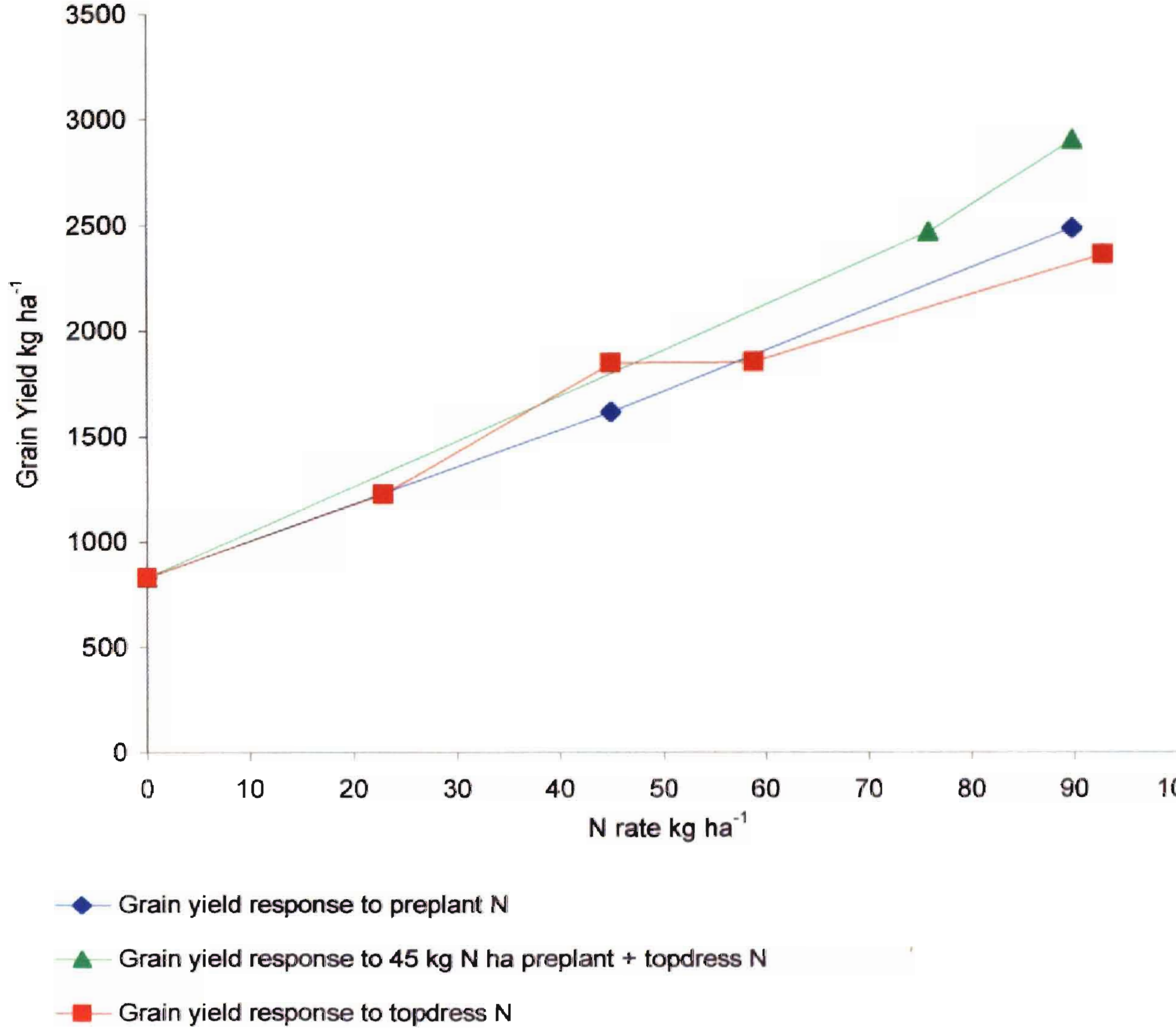
NUE of preplant, topdress and split application N rates at Efaw Upland 2001-2002.



† $RI_{NDVI}$ = 1.27
‡ $RI_{Harvest}$ = 1.57

## Appendix J

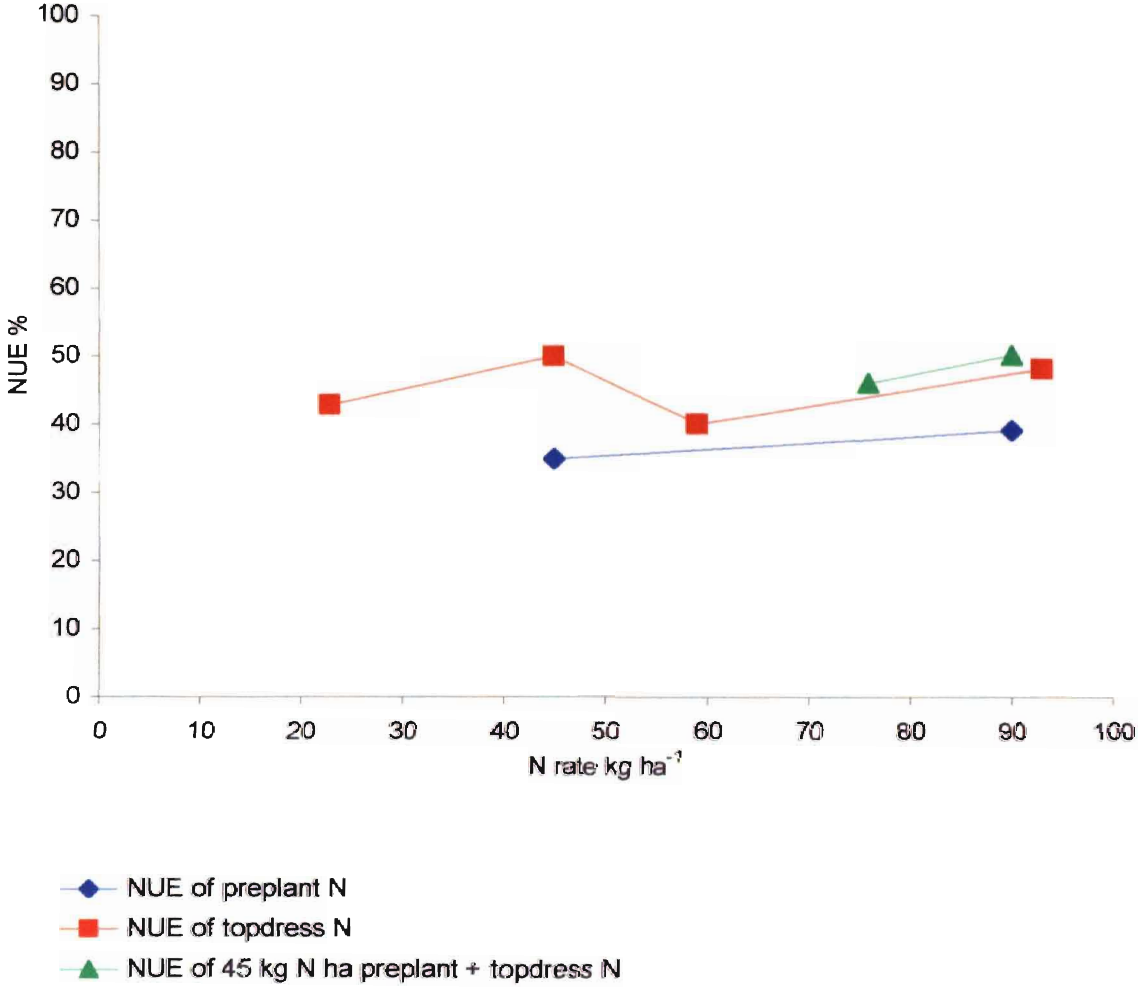
Grain yield of preplant, topdress and split application N rates at Efaw Upland 2002-2003.



† $RI_{NDVI}$ = 1.48
‡ $RI_{Harvest}$ = 2.99

# Appendix K

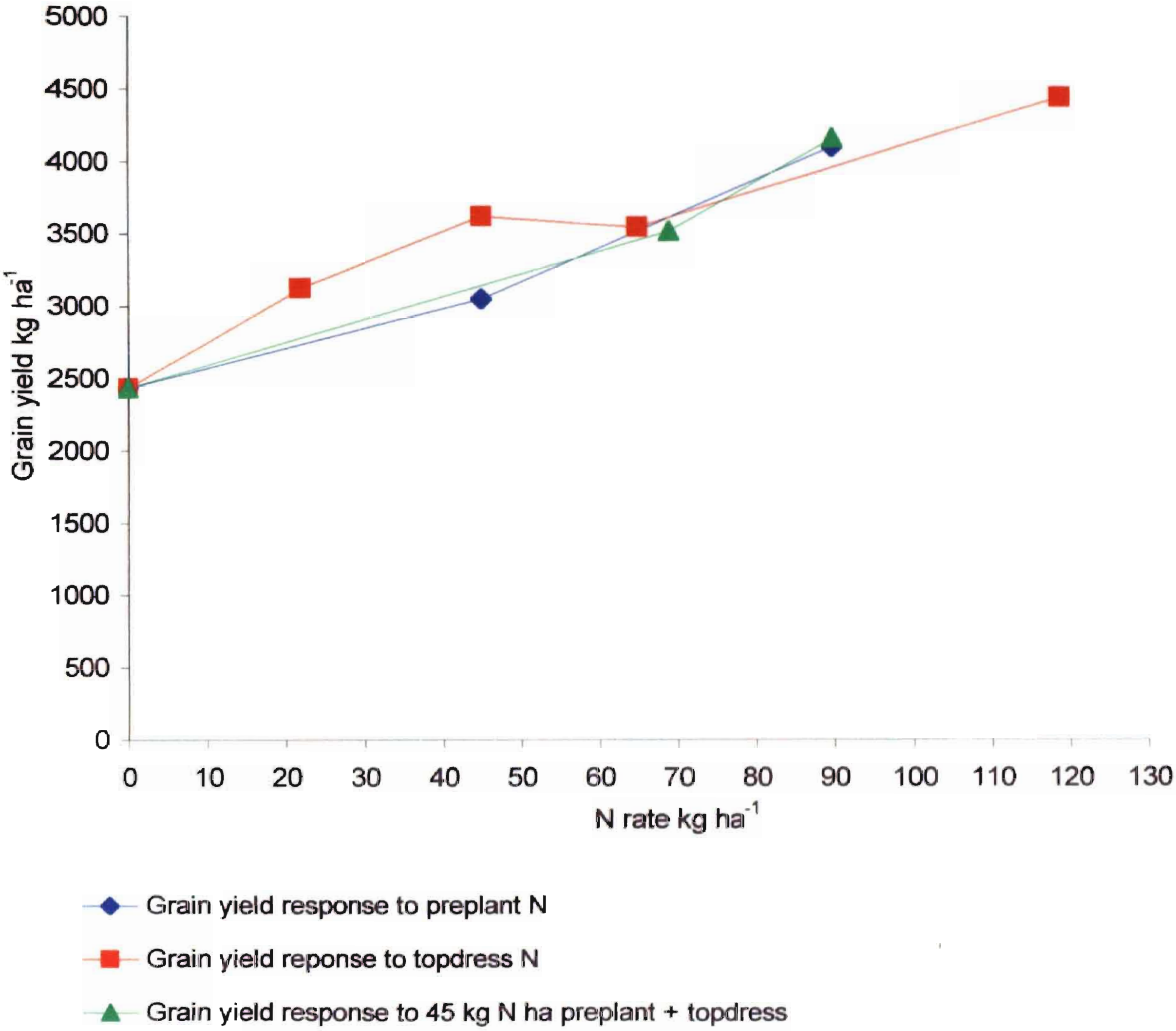
NUE of preplant, topdress and split application N rates at Efaw Upland 2002-2003.



† $RI_{NDVI}$ = 1.48
‡ $RI_{Harvest}$ = 2.99

## Appendix L

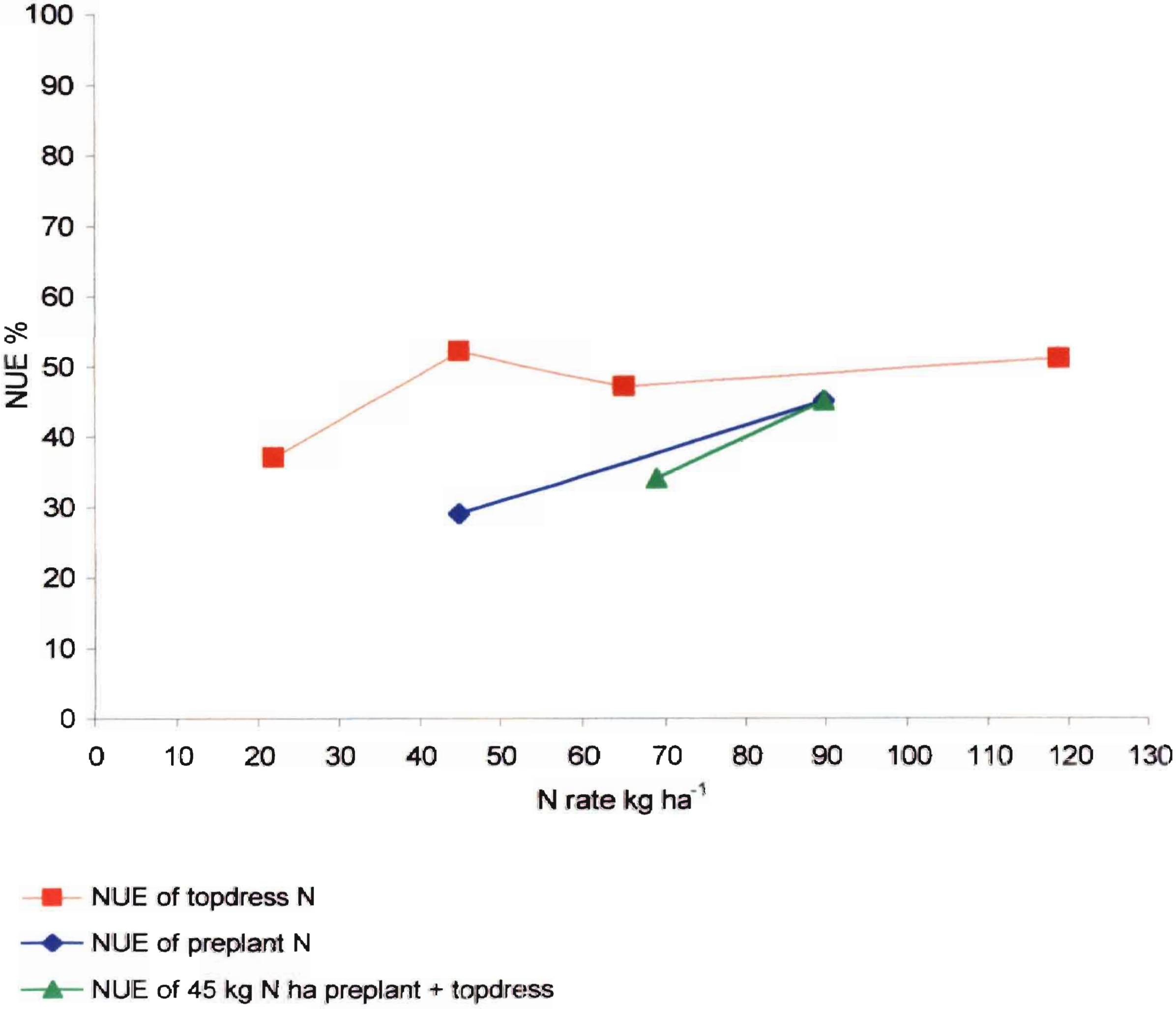
Grain yield of preplant, topdress and split application N rates at Lake Carl Blackwell 2002-2003.



† $RI_{NDVI}$ = 1.27
‡ $RI_{Harvest}$ = 1.68

# Appendix M

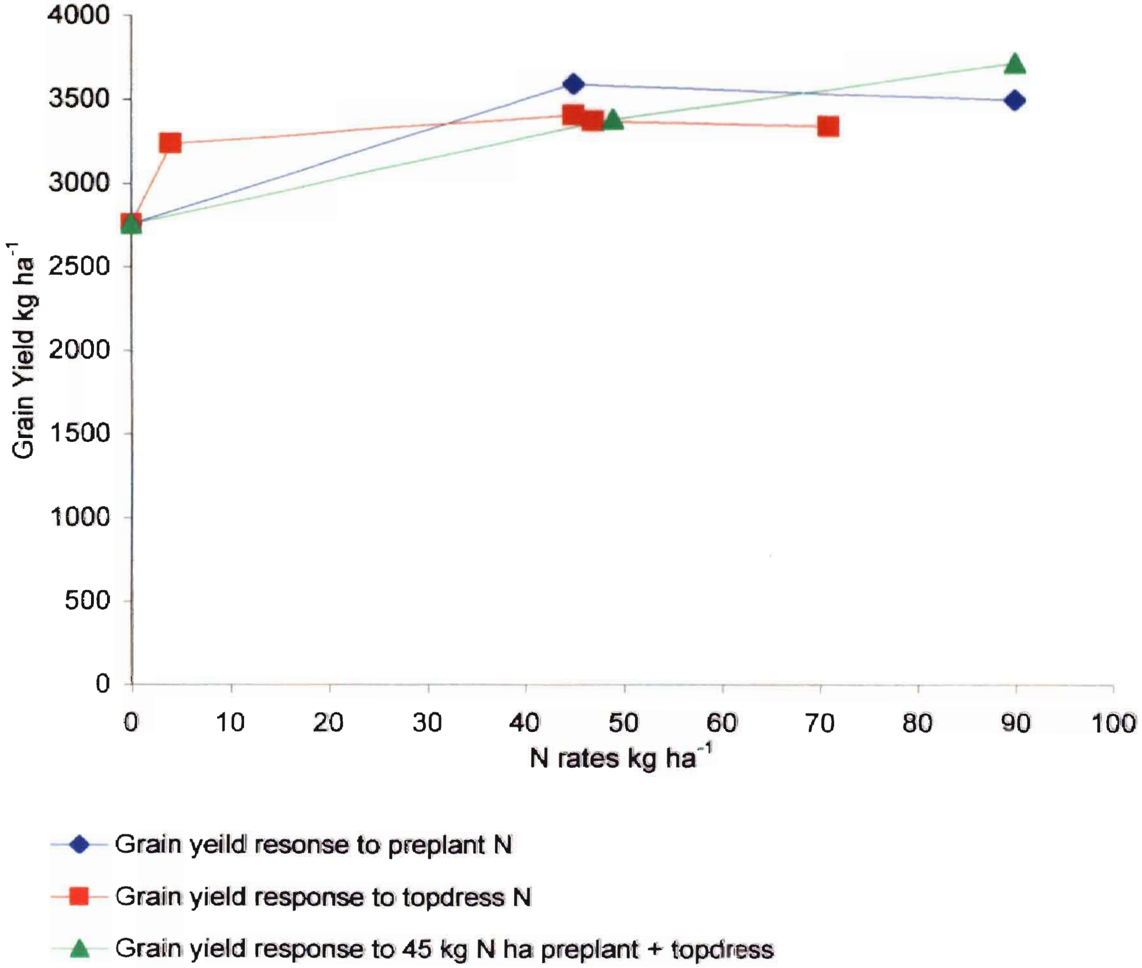
NUE of preplant, topdress and split N rates at Lake Carl Blackwell 2002-2003.



† $RI_{NDVI}$ = 1.27
‡ $RI_{Harvest}$ = 1.68

## Appendix N

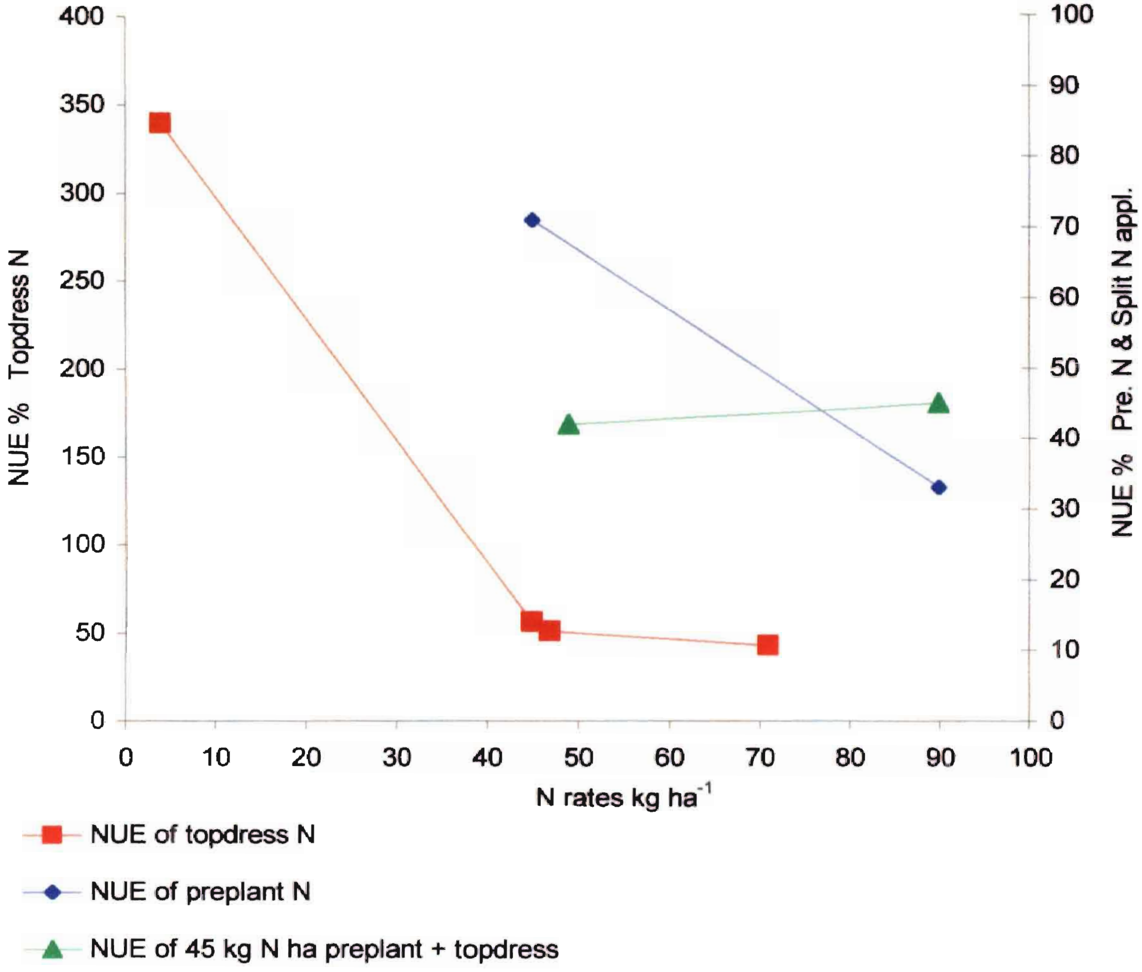
Grain yield of preplant, topdress and split application N rates at Perkins 2002-2003.



† $RI_{NDVI}$ = 1.06
‡ $RI_{Harvest}$ = 1.26

## Appendix O

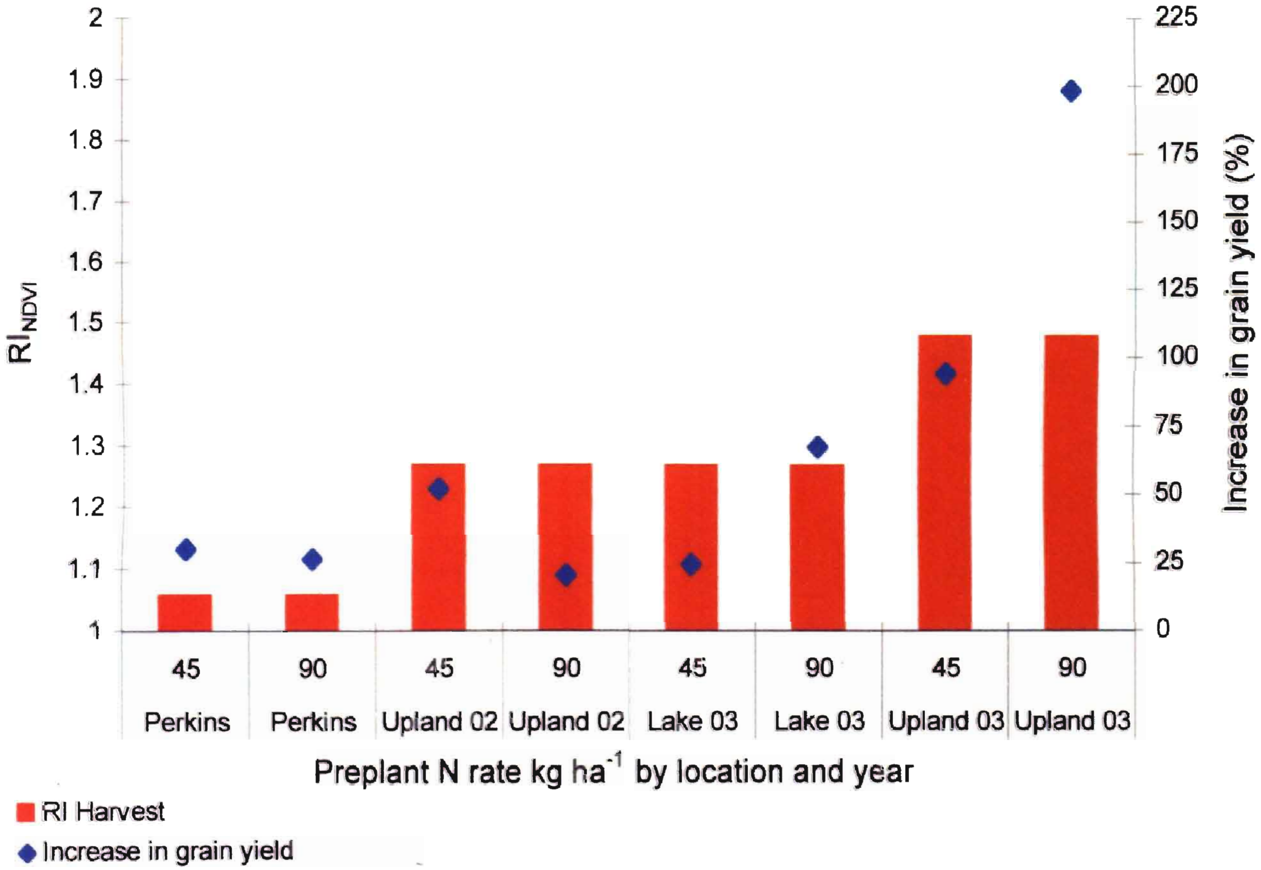
NUE of preplant, topdress and split application N rates at Perkins 2002-2003.



† $RI_{NDVI}$ = 1.06
‡ $RI_{Harvest}$ = 1.26

## Appendix P

Percent increase in grain yield by preplant N and $RI_{NDVI}$ of four N responsive sites for 2001-2003 crop years.



† Tipton site was omitted due to a late freeze occurring over a month after topdress N application.

# Appendix Q

Soil test data taken at harvest of check plots at four sites during 2002-2003.

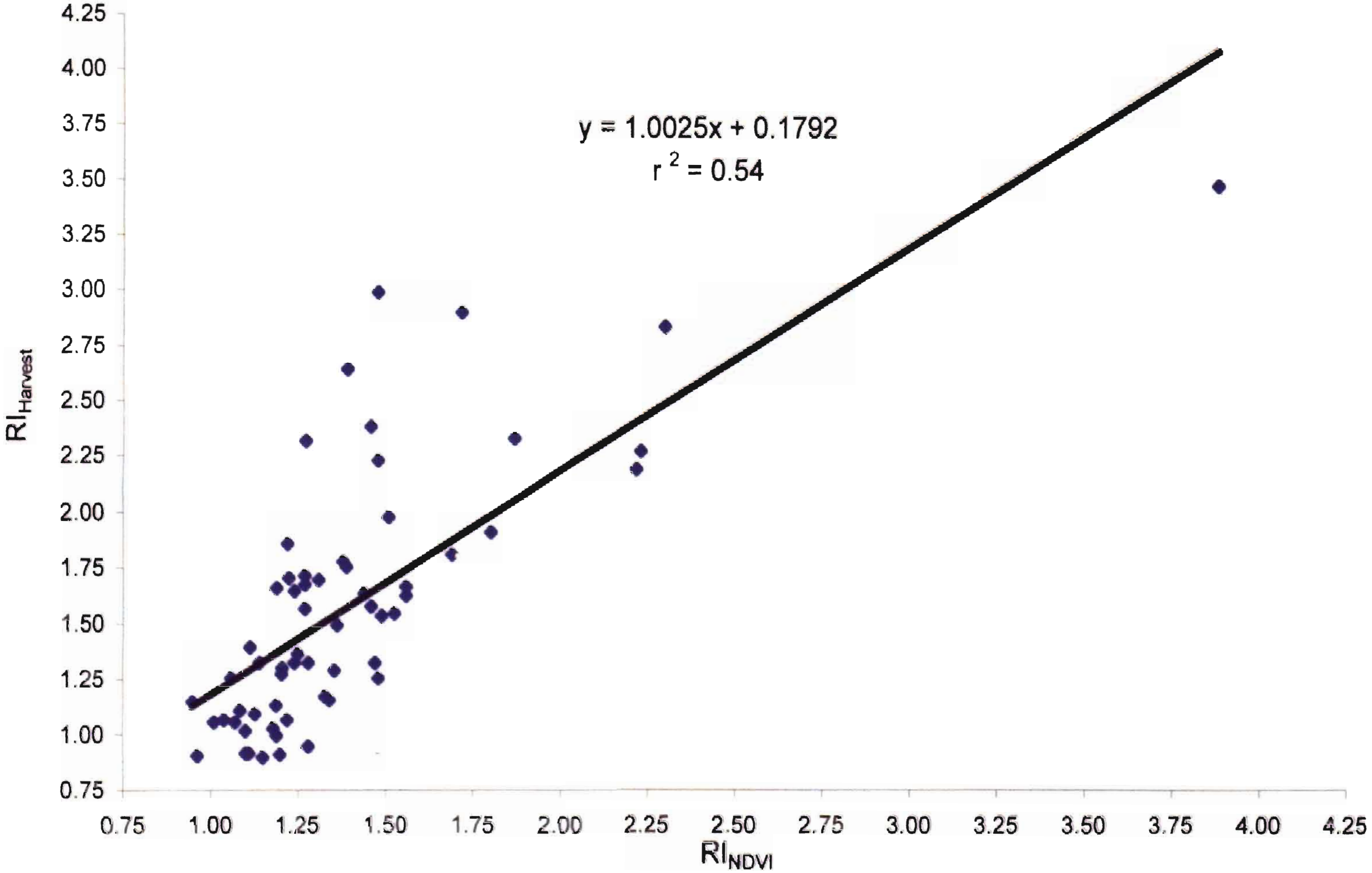
2002-2003 crop year

| Location | $NH_4$-N | $NO_3$-N | P | K | pH |
|---|---|---|---|---|---|
| | mg kg$^{-1}$ | | | | |
| Tipton | | | | | |
| 0-15 cm | 8 | 1 | 12 | 21 | 7.00 |
| 15-30 cm | 8 | 1 | 11 | 21 | 7.42 |
| Classification: Tipton silt loam : fine-loamy, mixed, thermic, Pachic Argiustoll | | | | | |
| Perkins | | | | | |
| 0-15 cm | 7 | 3 | 22 | 26 | 5.98 |
| 15-30 cm | 8 | 1 | 8 | 8 | 5.33 |
| Classification: Teller sandy loam: fine-loamy, mixed, thermic Udic Argstoll | | | | | |
| Lake Carl Blackwell | | | | | |
| 0-15 cm | 7 | 1 | 30 | 31 | 5.72 |
| 15-30 cm | 8 | 1 | 15 | 14 | 6.14 |
| Classification: Port-oscar: silt loam, fine-silty, mixed, super active, thermic Cumulic Haplustolls | | | | | |
| Efaw Upland | | | | | |
| 0-15 cm | 8 | 1 | 20 | 21 | 6.18 |
| 15-30 cm | 6 | 1 | 7 | 4 | 6.82 |
| Classification: Norge soil series: Fine-silty, mixed, thermic Udic Paleustolls | | | | | |

† $NH_4$-N and $NO_3$-N – 2 *M* KCl extraction
‡ P and K – Mehlich III extraction
§ pH – 1:1 soil:water

## Appendix R

Relationship between $RI_{NDVI}$ measured between Feekes 4-6 and $RI_{HARVEST}$ over 62 different locations and six years (1998-2003).



# VITA ②

## Paul James Hodgen

Candidate for the Degree of

Master of Science

Thesis: RELATIONSHIP BETWEEN THE RESPONSE INDEX DETERMINED IN-SEASON AND AT HARVEST AND THEIR USE FOR DETERMINING TOPDRESS NITROGEN RATES IN WINTER WHEAT

Major Field: Plant and Soil Sciences

Biographical:

Education: Graduated from North Putnam Jr./Sr. High School, Bainbridge, Indiana in June of 1997; received Bachelor of Science degree in Agronomy from Oklahoma State University, Stillwater, Oklahoma August 2001. Completed the requirements for the Master of Science degree with a major in Plant and Soil Sciences at Oklahoma State University in December, 2003.

Experience: Employed as a farm laborer for Hodgen Farms from 1992 to 1997, Roachdale, Indiana. Employed as a crop consultant for Crop Quest during the summer of 2000, Hutcheson, Kansas. Employed as project assistant by the Soil Fertility project from 2000 – 2001; Department of Agronomy as a graduate research assistant June 2001- Present.

Professional Memberships: American Society of Agronomy, Soil Science Society of America