MID-SEASON RECOVERY TO NITROGEN STRESS
IN WINTER WHEAT

By

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NOMENCLATURE

CV	Coefficient of variation
FNR	Fertilizer N requirement = $(GNUP_{YPN} - GNUP_{YP0})/0.60$
ρ_{NIR}	=Fraction of emitted NIR radiation returned from the sensed area (reflectance)
ρ_{Red}	=Fraction of emitted Red radiation returned from the sensed area (reflectance)
GDD	Growing Degree Days = $T_{min} + T_{max}/2 - 4.4$ ˚C
$GNUP_{YP0}$	Predicted grain N uptake at $YP_0 = YP_0 * PGN$.
INSEY	In-Season Estimated Yield= NDVI (Feekes 4 to 6)/ days from planting to sensing (days with GDD>0) = YP_0
NDVI	= $(\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + \rho_{Red})$
NUE	Nitrogen use efficiency
PGN	Calculate predicted grain N uptake at $YP_N(GNUP_{YPN})$, average percent N in the grain multiplied by YP_N: $GNUP_{YPN} = YP_N * PNG$
RI_{NDVI}	= NDVI from plots receiving adequate but not excessive preplant N, divided by the NDVI from the check plot where preplant N may or may not have been applied
$RI_{Harvest}$	=Maximum observed grain yield (treatment average with N fertilizer) divided by the observed grain yield from plots where no N was applied either preplant or topdress
SED	Standard error of the difference between two equally replicated means
YP_{Max}	=Maximum obtainable yield level for a specific environment determined by the farmer, or previously defined as a biological maximum by research agronomists for that crop, and for that region (units: Mg ha^{-1})

YP_0 = Predicted potential grain yield based on growing conditions up to the time of sensing, that can be achieved with not additional (todress) N fertilization (units: Mg ha^{-1})

YP_N = Predicted or potential yield that can be attained with added N (YP_N) fertilization based both on the in-season response index (RI_{NDVI}) computed as follows: units: (YP_N in Mg ha^{-1})

$$YP_N = (YP_0)*RI_{NDVI}$$

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ABSTRACT

Winter wheat yields are directly affected by the amount of nitrogen (N) that is available to them for growth. Past research has indicated that spring application of N is more effective than fall application for winter wheat. This experiment was conducted to determine if potential yield reductions from early season N stress can be corrected using in-season N applications. Three experimental sites for two growing seasons (6 site - years) were used to evaluate 3 preplant N rates (0, 45, and 90 kg ha^{-1}) and a range of in-season topdress N rates. Topdress N amounts were determined using a GreenSeeker^{TM} hand held sensor and an algorithm developed at Oklahoma State University. Even when early season N stress was present (0-N preplant) N applied topdress at Feekes 5 resulted in maximum or near maximum yields at 4 of 6 sites when compared to other treatments receiving both preplant and topdress N.

INTRODUCTION

As environmental and economical issues become a concern, it is important for action to be taken to address these important issues. Fertilizer is one of the major controversial environmental issues in today's world. Vidal et al. (1999) stated that the application of nitrogen (N) at rates exceeding plant utilization represents an unnecessary input cost for wheat producers and can harm aquatic and terrestrial environments.

Oklahoma State University (OSU), jointly with N-Tech industries, developed a sensor-based technology which has the ability to apply fertilizer to each 0.4 m^2 and that can increase yield and reduce excess application of (N) fertilizer. Oklahoma State University has a challenging job of continually teaching people how to better use and understand the new technology of precision agriculture. In order to do this, OSU needs to continue to evaluate and improve this technology to fit farmers and the environmental needs of our world.

The components of this work are as follows: YP_0 = Predicted potential grain yield, (which is the grain yield achievable with no additional N fertilization) from the grain yield in-season estimate of yield (INSEY) equation, where; INSEY = NDVI (Feekes 4 to 6)/days from planting to sensing (days where GDD>0). Units are Mg ha^{-1}. NDVI = Normalized difference vegetative index. YP_N = Determine the predicted yield that can be attained with added N (YP_N) fertilization based on both the in-season response index (RI_{NDVI} = NDVI collected from growing winter wheat anytime from

Feekes 4 to Feekes 6 in non-limiting fertilized plots divided by NDVI in a parallel strip receiving the farmer preplant N rate) and the potential yield achievable with no added N fertilization, computed as follows: (YP_N units in Mg ha^{-1}) $YP_N = (YP_0) * RI_{NDVI}$

Current methods of determining N fertilization rates in cereal production systems are determined by subtracting soil test N from a specified yield goal-based N requirement. The yield goal represents the best achievable yield in the last 4 to 5 years (Raun et al., 1999; Raun et al., 2001). There are, however, more precise and efficient ways of obtaining fertilizer recommendations to maximize yield and minimize cost. Following extensive soil sampling, optical sensor measurements of plants, and geostatistical analysis, several authors reported that the spatial scale of N availability was at 1m^2 and that each square meter needed to be treated independently (Raun et al., 1998; Solie et al., 1999; Raun et al., 2002). When N management decisions are made on areas of 1m^2, the variability that is present at that resolution can be detected using optical sensors (measuring NDVI) and treated accordingly with foliar application of N (Solie et al., 1996; Stone et al., 1996; Raun and Johnson, 1999), which increases nitrogen use efficiency (NUE) (Stone et al., 1996). Recently, methods for estimating winter wheat N requirements based on early-season estimates of N uptake and potential yield were developed (Lukina et al., 2001; Raun et al., 2002). Remote sensing collected by a modified daytime-lighting reflectance-sensor was used to estimate early-season plant N uptake. The estimate was based on a relationship between NDVI and plant N uptake between Feekes physiological growth stage 4 (leaf sheaths lengthen) and 6 (first node of stem visible) (Large, 1954; Stone et al., 1996; Solie et al., 1996). NDVI was calculated using the following equation: $NDVI = (\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + \rho_{Red})$

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

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

Increasing NUE by just 20% would result in a savings exceeding of $4.7 billion per year (Raun and Johnson, 1999). Improving NUE will decrease the risk of $N0_3$-N contamination of inland surface and ground water (Stone et al., 1996; Raun and Johnson, 1999), as well as the hypoxia in specific oceanic zones which are believed to be caused by excess N fertilizer (Malakoff, 1998; Raun and Johnson, 1999).

Raun et al. (2002) stated that measuring the quantitative response to fertilizer N is achievable for a given area. This is why the N fertilization optimization algorithm (NFOA) was developed. It determines the prescribed N rate needed for each $1m^2$ based on predicted yield potential without added N fertilizer (YP_0) and the specific response index (RI) for each field. Johnson and Raun (2003) defined RI as the amount of yield response to expect from an application of fertilizer-N compared to yield with no additional N, and that may range from 1 to as high as 4. Raun et al. (2002) explained that the NFOA accounts for spatially variable potential yield, early season N uptake, and responsiveness of the crop to N input. The algorithm calculations are as follows:

1.) Predict YP_0 from the equation for grain yield and INSEY, where

INSEY = NDVI (Feekes 4-6)/ days from planting where growing degree days (GDD) > 0 [$GDD= (T_{min} + T_{max})/2 - 4.4^{o}$ C, where T_{min} and T_{max} represent daily ambient high and low temperatures].

Lukina et al. (2001), showed that a single equation could be used to predict grain yield over a wide production range (0.5-6.0 Mg ha^{-1}), diverse sites, and with differing planting and harvest dates. Dividing NDVI at Feekes 5 (excellent predictor of early-season plant N uptake) by the days from planting to the NDVI sensing date resulted in an index that would approximate N uptake per day.

2.) Predict the magnitude of response to N fertilization, in-season RI (RI_{NDVI}), computed as: NDVI collected from growing winter wheat anytime from Feekes 4 to Feekes 6 in non-limiting fertilized plots divided by NDVI in a parallel strip receiving the farmer preplant N rate.

The RI_{NDVI} has been found to be highly correlated with the RI at harvest ($RI_{Harvest}$), which is similarly computed by dividing the highest mean grain yield of the N rich treatment from the mean grain yield of 0-N treatment (check plot) (Mullen et al., 2001). The farmer preplant N rate could range anywhere from zero to a rate for non-N limiting conditions. (Raun et al., 2002).

3.) Determine the predicted Yield with additional N (YP_N) based both on RI_{NDVI} and the YP_0 as follows:

$YP_N = YP_0 * RI_{NDVI}$

The RI_{NDVI} was limited so as not to exceed 3.0 and YP_N was similarly limited not to exceed the maximum obtainable yield (YP_{max}). The YP_{max} was determined by the farmer, or by measuring the maximum NDVI in the N rich strip(N applied at adequate but not excessive rates preplant) (W. Raun, J. Solie, personal communication, July 2004, and reported on http://nue.okstate.edu) and using that value to calculate the maximum possible yield using the yield potential equation. The YP_{Max} can also be defined as a biological maximum for a specific cereal crop grown within a specific region and under defined management practices (e.g., YP_{max} for dry land winter wheat produced in central Oklahoma would be 7.0 Mg ha^{-1}). The RI_{NDVI} was capped at 3.0 as in-season applications of N would unlikely lead to YP_N being more than three times greater than baseline YP_0.

4.) Calculate predicted grain N uptake (PNG) at YP_N ($GNUP_{YPN}$), average percent N in the grain multiplied by YP_N: $GNUP_{YPN} = YP_N * PNG$

5.) Calculate PNG at YP_0, average percent N in the grain multiplied by YP_0: $GNUP_{YP0} = YP_0 * PNG$.

6.) Determine in-season fertilizer N requirement (FNR):

$FNR = (GNUP_{YPN} – GNUP_{YP0})/0.60$

A divisor of 0.60 in the above equation is used because the theoretical maximum NUE of an in-season N application is approximately 60%.

The use of active growing days from planting and NDVI (estimate of total N uptake and or biomass) in computing INSEY allows integration of the effects of both winter and spring growing conditions and date of planting. The INSEY index is essentially the rate of N uptake (kilograms of forage N assimilated per day) by the plant. This approach is consistent with work showing the relationship between above ground plant dry weight and cumulative GDD (Rickman et al., 1996). Further analyses showed that a reliable INSEY could be obtained by dividing NDVI by the days from planting to sensing date (where $GDD > 0$) (Raun et al., 2002; Mullen et al., 2003). Mullen et al.

(2003) also stated that the INSEY was used to estimate N uptake in the grain based on a predicted yield level. Finally, using predicted wheat N uptake (measured by NDVI) at Feekes 5 (excellent predictor of early-season plant N uptake) and projected grain N uptake from INSEY, topdress fertilizer N rates have been determined (grain N uptake minus early season plant N uptake) (Lukina et al., 2001).

Johnson et al. (2000), defined the harvest response index ($RI_{Harvest}$):

$RI_{Harvest}$ = (highest mean yield N-treatment)/(mean yield check treatment).

The use of $RI_{Harvest}$ does not allow for in-season adjustment of N. In-season sensor measurements of NDVI as an indicator of wheat N uptake between plots receiving N and those not receiving N can be used in the same way using the following equation:

RI_{NDVI} = (highest mean NDVI N treatment)/(mean NDVI check treatment).

Mullen et al. (2003) concluded that basing fertilizer N rates on INSEY and RI_{NDVI} may help optimize in-season fertilizer application, which in turn could increase NUE and yield. The objective of this work was to determine if RI_{NDVI} could accurately predict $RI_{Harvest}$ at Feekes growth stages 5, 9, 10.5, and 11.2. They also found that RI_{NDVI} measured at Feekes 5 was highly correlated to $RI_{Harvest}$. Mullen et al. (2003) recognized that after remote sensing data is collected yield enhancing and limiting factors may occur that result in underestimation or overestimation of $RI_{Harvest}$ by RI_{NDVI}. For example, in 1999, early spring rains after a dry fall planting period improved post sensing growing conditions. Timely rainfall may have increased the N response resulting in a larger $RI_{Harvest}$ than predicted by RI_{NDVI}. The objectives of this work were to determine if potential yield reductions from early stress can be corrected by using in-season fertilizer applications, and to evaluate the relationship between RI_{NDVI} and $RI_{Harvest}$ over years and locations.

MATERIALS AND METHODS

Three experimental sites were selected for this study: one located with a cooperating farmer at Covington, OK (Kirkland- Renfrow silt loam, fine, mixed, superactive, thermic Udertic Paleustolls), one at Stillwater Research Station Lake Carl Blackwell, Oklahoma (Port-oscar silt loam, fine-silty, mixed, super active, thermic Cumulic Haplustolls), and one located at Tipton Oklahoma, OSU research station, (Tillman-Hollister silt loam; fine-loamy, mixed, thermic, Pachic urgiusoll). A randomized complete block design was employed with fifteen treatments and 4 replications. Plot size was 3.05 x 6.1m with 6.1m alleys. Three preplant N rates (0, 45, and 90 kg N ha^{-1}) were evaluated with all preplant N applied as ammonium nitrate (34-0-0). Topdress N application rates were determined utilizing the N fertilization optimization algorithm (NFOA) (Raun et al., 2002) with four different RI values. The RI values evaluated were 1.0, 1.3, 1.6, and 2.0. Algorithms differed for 2003 and 2004 whereby CVs were used in 2004 to alter yield potential achievable with N fertilization (http://www.nue.okstate.edu). Response index was calculated as reported by Johnson and Raun (2003). Spectral reflectance was measured using a GreenSeeker^{TM} Hand Held Optical Sensor (N-tech Industries) that collected NDVI measurements. This device uses a patented technique to measure crop reflectance and calculate NDVI. The unit senses a 0.6 x 0.01 m spot when held at a distance of approximately 0.6 to 1.0 m from the illuminated surface. The sensed dimensions remain approximately constant over the height range of the sensor. The sensor unit has self-contained illumination in both the red

(650 ± 10 nm FWHM) and NIR (770 ± 15 nm FWHM) bands (FWHM = full width at half maximum). The device measures the fraction of the emitted light in the sensed area that is returned to the sensor; the fractions are used within the sensor to compute NDVI.

The sensor unit is designed to be “hand-held” and measurements are taken as the sensor is passed over the crop surface. The sensor samples at a very high rate (approximately 1000 measurements per second), and averages measurements between outputs. The sensor outputs NDVI at a rate of 10 readings per second. Reflectance readings were collected throughout the growing season. The NDVI readings taken for the topdress N fertilization application from all experiments were collected post-dormancy. The date when readings were collected generally corresponded to Feekes growth stage 5 (pseudo-stem, formed by sheaths of leaves strongly erect) (Large, 1954). Topdress N was foliar applied to the whole plot using urea ammonium nitrate (UAN, 28-0-0) with a Solo backpack sprayer (amounts were calculated and then measured with a graduated cylinder). For the smaller rates, a pulse modulated sprayer designed by OSU was used.

Winter wheat grain was harvested using a self-propelled Massey-Ferguson 8XP combine. An area of 2.0 by 6.1 meters was harvested from the middle of each plot, and a Harvest Master yield-monitoring computer installed on the combine recorded yield data. A sub-sample of grain was taken and dried in a forced-air oven at 66^{o}C ground to pass a 100 μm screen, and analyzed for total N content using a Carlo-Erba NA-1500 Dry Combustion analyzer (Schepers et al., 1989). Statistical analysis was preformed using SAS (SAS, 2001). Treatment structure for 2002-2004 is reported in Tables 1 and 2. Table 1, the title Topdress N * RI means the column underneath is calculated using the

RI for treatment 2,7,and 12, and treatments 3-5,8-10, and 13-15 are calculated using RI times a fixed number. For Table 2, the column with topdress N * RI_CV means the same except for the _CV, which means that the CV was considered in the fertilizer rate. Initial soil samples, chemical characteristics and classification of soils is reported in Table 3. Field activities and dates are listed in Table 4. Average NDVIs and CV of NDVI measurement readings are reported in Tables 5 and 6.

RESULTS

Covington, 2003

At Covington in 2003 where no topdress N was applied, there was a linear increase in wheat grain yield with increasing preplant N (treatment 1 (0 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress) =3170 kg ha^{-1}, 6 (45 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress)=4527 kg ha^{-1}, 11 (90 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress) = 5234 kg ha^{-1} (Table 7). At this site, there was also an increase in wheat grain yield for topdress N rates whether or not preplant N had been applied. However, the yield increases from topdress N diminished with increasing preplant N. Maximum yields were not achieved at this site from mid-season topdress N applications in plots receiving no preplant N when compared to the plot that achieved maximum yield, which was not the N- rich plot (treatment 11). The plot that achieved maximum yield was treatment 10 (45 kg ha^{-1} preplant plus RI times 2.0 kg ha^{-1} topdress). It should be noted that even with early N stress, topdress N rates (treatment 5(0 kg ha^{-1} preplant plus RI times 2.0 kg ha^{-1} topdress) = 5271 kg ha^{-1}) did produce an equal yield to the preplant non N limiting plot (treatment 11, 5234 kg ha^{-1}), but that was still less than maximum yield (treatment 10 (45 kg ha^{-1} plus RI times 2.0 topdress) , 5875 kg ha^{-1}). The "catch-up" effect being evaluated in this work states the following: Can maximum yields be produced when no N is applied preplant and N applications are delayed until February or March? At this site, it was not possible to "catch-up" where 0-N was applied preplant plus a mid-season topdress N application (treatment 10 = 5875 kg ha^{-1}) (Table 7).

The coefficient of variation (CV) from sensor readings in treatments 1, 6, and 11 at the time topdress N was applied declined as preplant N increased (23, 21, and 20) (Table 5). Recent work has shown that when CVs are < 18, “catch-up” is possible (catch-up: waiting to apply all nitrogen topdress and still achieving maximum yields) (http://nue.okstate.edu). Consistent with this work, CVs were all > 18 at this site indicating that “catch up” was not going to be possible and that was confirmed (Table 5,7).

Nitrogen use efficiency was the greatest for the 0 N preplant treatments plus mid-season applied N (treatments, 1-5) (Table 7), but it should be noted that NUE’s were generally quite high at this site. Past results of OSU’s algorithm show a consistent increase in NUE (http://nue.okstate.edu).

The RI estimated using in season NDVI readings was under estimated at this site ($RI_{NDVI} = 1.27$ and $RI_{Harvest} = 1.7$, Table 7). It is possible that the N rich treatment (11) may not have received enough preplant N to accurately estimate RI_{NDVI}. RI_{NDVI} over time for 2003 did not change much from Feekes 3 to Feekes 5 ($RI_{NDVI} = 1.18$, 1.24, and 1.27) (Table 4). The $RI_{Harvest}$ was much higher than the RI_{NDVI}’s ($RI_{Harvest} = 1.7$, Table 4, 7).

Lake Carl Blackwell, 2003

At Lake Carl Blackwell in 2003, there was a linear increase in grain yield for N applied preplant (treatment 1 (0 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress) = 3207 kg ha^{-1}, 6 (45 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress)= 3579 kg ha^{-1}, 11 (90 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress)= 4276 kg ha^{-1}) (Table 8). There was an increase in grain yield for topdress N rates for the 45 kg ha^{-1} preplant rates, but no increase from topdress N where

90 kg ha^{-1} was applied preplant. Maximum yields were achieved at this site from mid-season topdress N applications in plots receiving 0 preplant N in comparison to the maximum yielding plots (treatments 4 (0 kg ha^{-1} plus RI times 1.6 kg ha^{-1} topdress) = 4453) and 5 (0 kg ha^{-1} preplant plus RI time 2.0 kg ha^{-1} topdress) = 4453 kg ha^{-1}) (Table 8). At this site, maximum yields were achievable with no preplant N plus a topdress rate for the maximum yielding plot (treatment 10 (45 kg ha^{-1} preplant plus RI times 2.0 kg ha^{-1} topdress) 4546 kg ha^{-1}) and also for the N rich plot treatment 11 (90 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress, 4276 kg ha^{-1}).

The CVs (9, 9, and 7) from sensor readings in treatments 1, 6, and 11 at the time topdress N was applied tended to decline as preplant N increased (Table 5). Consistent with previous work (http://nue.okstate.edu), CVs were < 18, and it was expected that "catch-up" would be possible, which was confirmed (4453 kg ha^{-1} treatments 4 and 5 versus 4537 kg ha^{-1}, treatment 15 (90 kg ha^{-1} preplant plus RI times 2.0 kg ha^{-1}) (Table 5, 8).

The NUE at this site varied across all treatments. The greatest NUE for this site was achieved when 90 kg ha^{-1} was applied preplant. In general, the 0 preplant plus topdress treatments had the highest NUE with the exception of treatment 11 (Table 8).

The RI estimated using in season NDVI readings were slightly underestimated $RI_{Harvest}$ at this site (RI_{NDVI} = 1.14 and $RI_{Harvest}$ = 1.3, Table 8). RI_{NDVI} over time for 2003 did not change much from Feekes 3 to Feekes 4 (RI_{NDVI}=1.15, 1.13, and 1.14) (Table 4). The $RI_{Harvest}$ were higher than the RI_{NDVI}'s ($RI_{Harvest}$= 1.3) (Table 4, 8).

Tipton, 2003

At Tipton in 2003 where 0 topdress N was applied, there was a linear response to N (treatment 1 (0 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress = 1357 kg ha^{-1}, treatment 6 (45 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress = 1264 kg ha^{-1}), treatment 11 (90 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress = 2082 kg ha^{-1}) (Table 9). Also, there was an increase in wheat grain yield whether or not preplant N was applied (Table 9). Maximum yields were not achieved at this site from mid-season topdress N applications in plots receiving 0 preplant N in comparison with the maximum yielding plot (treatment 13, 90 kg ha^{-1} preplant plus RI times 1.3 kg ha^{-1} topdress). At this site, it was not possible to "catch-up" with no preplant plus a topdress N application even though CVs were relatively low (Tables 5 and 9). However, it should be noted that "catch-up" was possible if treatment 5 (0 preplant plus RI times 2.0 kg ha^{-1}) treatment was compared to the (treatment 11) 90 preplant plus 0 topodress rate kg ha^{-1} (treatment 5 = 2278 kg ha^{-1} and treatment 11 = 2082 kg ha^{-1}).

The NUE was generally higher for the 90 kg ha^{-1} preplant treatments (Table 9).

Response index estimated using in season NDVI readings was the same as $RI_{Harvest}$ (RI_{NDVI} = 1.49 and $RI_{Harvest}$ = 1.5) (Table 4, 9).

Covington, 2004

At Covington in 2004, there was a linear increase in wheat grain yield with increased N where no topdress was applied (treatment 1 = 1985 kg ha^{-1}, treatment 6 = 2846 kg ha^{-1}, and treatment 11 = 3751 kg ha^{-1}) (Table 10). At this site, there was a significant increase in wheat grain yield and N rates required to maximize yields diminished as preplant N rates increased. It should be noted that the highest yielding plot was a 0 preplant rate (treatment 5, Table 10), thus suggesting that “catch-up” was possible with respect to maximum yield and also with the N rich plot.

The CVs, for treatments 1, 6, and 11 were 18, 21, and 15 respectively (Table 6). Some of the CVs were ≤ 18 indicating that maximum yields could be achieved even when early season N stress was present (Table 6).

The NUEs were generally higher for the 90 kg ha^{-1} preplant treatments (Table 10), likely because this was a N responsive site.

The RI_{NDVI} was slightly over estimated at this site ($RI_{NDVI} = 2.02$ and $RI_{Harvest} = 1.89$) (Table 10). RI_{NDVI} over time for 2003 did not change from Feekes 3 to Feekes 4 (RI_{NDVI}=1.47, 2.19, 2.18, 2.02, 1.9 and 1.9) (Table 4). The $RI_{Harvest}$ slightly differed from RI_{NDVI}s ($RI_{NDVI} = 2.02$ and $RI_{Harvest}$=1.89) (Table 4, 10).

Lake Carl Blackwell, 2004

At Lake Carl Blackwell in 2004, there was a linear increase in wheat grain yield where 0 topdress N was applied (treatment 1 (0 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress = 3047 kg ha^{-1}, treatment 6 (45 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress = 3502 kg ha^{-1}, and treatment 11 (90 kg ha^{-1} preplant plus 0 kg ha^{-1} topdress = 3766 kg ha^{-1}) (Table 11). Wheat grain yield increased as topdress N rates increased. Maximum yields were achieved at this site from mid-season topdress N applications in plots receiving 0 preplant N (treatment 3, 0 preplant kg ha^{-1} plus RI times 1.3_CV = 3675 kg ha^{-1} versus treatment 11 = 3766 kg ha^{-1}), thus “catch-up” was possible for this site with 0 preplant plus topdress application in accordance with the highest yielding plot (Table 11).

The CVs varied once again at this site for treatments 1, 6, and 11 (18, 19, and 16, respectfully). Consistent with CVs being less than 18, "catch–up" was possible at this site, (Table 6).

The NUEs were generally higher for the 0 and 45 preplant kg ha^{-1} treatments (Table 11).

Response index estimated using in-season NDVI readings was the same as $RI_{Harvest}$ (RI_{NDVI} = 1.24 and $RI_{Harvest}$ = 1.24) (Table 11). RI_{NDVI} over time for 2004 varied from Feekes 3 to Feekes 8 (RI_{NDVI}=1.10, 1.10, 1.11, 1.24, and 1.22). The $RI_{Harvest}$ was the same as the RI_{NDVI} at fertlization (Table 4).

Tipton, 2004

At Tipton in 2004, there was a linear increase in wheat grain yield where 0 topdress N was applied. There was a significant increase in grain yield with applied topdress N rates for the 0 and 45 kg ha^{-1} preplant rates with no increase from topdress N for the 90 kg ha^{-1} preplant rates. Maximum yields were achieved at this site from mid-season topdress N applications in plots receiving 0 preplant N with respect to the maximum yielding plot (treatment 8, 45 kg ha^{-1} preplant plus RI times 1.3_CV = 4845 kg ha^{-1}). Catch-up was also possible with respect to the N rich plot (treatment 11), since treatment 5 out yielded the N rich plot. At this site, "catch-up" was possible with 0 preplant N plus topdresss N applications in accordance with the highest yielding plots (Table 12).

The CV was low at this site even when early season N stress was encountered (Table 6).

The NUEs were generally higher for the plots receiving 0-N preplant plus topdress N (Table 12).

Response index estimated using in season NDVI readings was under estimated for this site (RI_{NDVI} = 1.49 and $RI_{Harvest}$ = 1.68, Table 12) RI_{NDVI} over time for 2004 changed from Feekes 3 to Feekes 5 (RI_{NDVI}=.92, 1.09, and 1.49) (Table 4). The $RI_{Harvest}$ was different than the RI_{NDVI} was at fertilization (Table 4, 12).

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DISCUSSION

In this study, 6 locations had a linear increase in wheat grain yield from topdress N applied to plots receiving 0-N preplant (Tables 7-12). Also, 4 of the 6 sites had a increase in wheat grain yield for the topdress N rates whether or not preplant N had been applied (Tables 7-12). Melaj et al. (2003) stated that N uptake increased around the time of maximum crop growth, so application of fertilizer at tillering would increase N fertilizer recovery by the crop. Early season plant N uptake can lead to increased plant N volatilization (Lees et al., 2000). Boman et al. (1995) states that a management strategy to reduce N loss would be to apply enough fertilizer N in the fall to establish the crop and apply the remaining N requirement in the late winter or early spring before rapid growth begins. Warm soil temperatures after this time would coincide with rapid wheat growth and also increase nutrient demand.

If N application is made prior to the period of rapid uptake and growth, there is a potential for increased N uptake and N use efficiency (Sowers et al., 1994, and Johnston and Fowler, 1999). At all three locations in 2003, the highest NUEs were found where preplant N was applied. In 2004, 0-N preplant plus topdress N treatment generally had improved NUEs. At two sites where early N stress was severe, preplant N applications were superior to 0-N preplant plus topdress N. Woolfolk et al. (2002) and Gauer et al.(1992) agree that increasing grain protein by applying higher fertilizer N rates is relatively inefficient (NUE decreases with increasing N level), especially under dry soil conditions. In our work, there was one exception at Lake Carl Blackwell, 2003 that was treatment 11 (Table 8). Treatment 11's NUE was almost the same as the highest NUE for the site (treatment 2 = 53 and treatment 11 = 52). Wuest and Cassman, (1992 a) and Wuest and Cassman, (1992 b), indicated that a late-season N application has greater uptake efficiency and is more effective in increasing grain N levels than N applied at planting. Alternatively, they noted that preplant N was more effective in increasing grain yields.

This work addresses an interesting question. Can N applications be delayed until mid-season in winter wheat without decreasing wheat grain yields? The majority of farmers in this region of the wheat belt apply all of their fertilizer N at planting. Although topdress N applications have become more popular, it is still a common practice to apply anhydrous ammonia in the fall at rates exceeding 110 kg N ha^{-1}. The ease of applying liquid UAN topdress and the advent of larger, 20-30 m wide applicators has assisted the extension of delaying fertilizer N until late February.

Because maximum yields were achieved at 4 of 6 sites where all N applied was delayed until Feekes 5, this work has use in both efficiency and environmental implications. Also, all 6 sites were able to catch-up with respect to the N-rich plots, however, it should be noted that 5 of the 6 N rich plots were not the maximum yielding plots. RI over time showed little to no change for 2003 across all three sites. However, in 2004, two of the three sites had a change in RI over time. By delaying fertilizer N applications until post dormancy, there is decreased risk of NO_3-N leaching and/or surface fertilizer N runoff when preplant applications are made to the surface without incorporation. Also, by applying fertilizer N to the foliage in late February, increased use efficiency can be realized (foliar N uptake) when compared to preplant soil applied N (N subject to NO_3-N leaching, immobilization, denitrification, surface volatilization, and early season plant N loss).

These results are not yet definitive concerning whether or not all N should be delayed until mid-season. The reason for this is because exceptional growing conditions occurred, whereby timely rainfall was received immediately following topdress fertilizer N applied, especially for 2004. Although not explicitly evaluated in other work conducted in Oklahoma, there have been dry springs where delayed topdress fertilizer N was not beneficial and maximum yields were not produced. This was evident in many of the GreenSeeker sensor experiments conducted by OSU in 1999, 2000, 2001, whereby the topdress N plots never achieved the same yields as what was found in the N Rich Strip (N applied at adequate but not excessive rates preplant) (W. Raun, J. Solie, personal communication, July 2004, and reported on http://nue.okstate.edu).

In this regard, a more complete data base is needed to better evaluate the effectiveness of delayed topdress N compared to N applied preplant and that should be a high priority for the OSU soil fertility project.

CONCLUSIONS

In 2002-2004, obtaining maximum wheat grain yields from topdress N applications in 0 N preplant plots was possible at four of the six locations. The CVs for the two sites that failed to reach maximum yield were higher than 18 and the CVs for the site where topdress N was applied to 0 N preplant plots that achieved maximum yield were below 18. Also, at three of the six sites, the RI estimated using in season NDVI readings was under estimated. Even when early season N stress was present (0-N preplant), N applied topdress at Feekes 5 resulted in maximum or near maximum yields at 4 of 6 sites when compared to other treatments receiving both preplant and topdress N. However, when compared to the conventional 90 kg ha^{-1} preplant N, mid-season N applied (0-N preplant) resulted in maximum yields at all 6 sites.

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Table 1. Treatment Structure for all 3-experimental sites, (Covington, Lake Carl Blackwell, and Tipton OK, 2002-2003.)

Treatment	Preplant N Rate (kg ha $^{-1}$)	Topdress N * RI	
1	0	YP_0	0
2	0	YP_N	RI
3	0	YP_N	RI * 1.3
4	0	YP_N	RI * 1.6
5	0	YP_N	RI * 2.0
6	45	YP_0	0
7	45	YP_N	RI
8	45	YP_N	RI * 1.3
9	45	YP_N	RI * 1.6
10	45	YP_N	RI * 2.0
11	90	YP_0	0
12	90	YP_N	RI
13	90	YP_N	RI * 1.3
14	90	YP_N	RI * 1.6
15	90	YP_N	RI * 2.0

* RI is the actual response index determined for that field.

Table 2. Treatment Structure for all 3-experiment sites, (Covington, Lake Carl Blackwell, and Tipton OK, 2003-2004.)

Treatment	Preplant N Rate (kg ha $^{-1}$)	Topdress N * RI	
1	0	YP_0 _ CV	0
2	0	YP_N _ CV	RI _ CV
3	0	YP_N _ CV	RI * 1.3 _ CV
4	0	YP_N _ CV	RI * 1.6 _ CV
5	0	YP_N _ CV	RI * 2.0 _ CV
6	45	YP_0 _ CV	0
7	45	YP_N _ CV	RI * CV
8	45	YP_N _ CV	RI * 1.3 _ CV
9	45	YP_N _ CV	RI * 1.6 _ CV
10	45	YP_N _ CV	RI * 2.0 _ CV
11	90	YP_0 _ CV	0
12	90	YP_N _ CV	RI * CV
13	90	YP_N _ CV	RI * 1.3 _ CV
14	90	YP_N _ CV	RI * 1.6 _ CV
15	90	YP_N _ CV	RI * 2.0 _ CV

* RI is the actual response index determined for that field.
* CV is the coefficient of variation of each plot.

Table 3. Initial surface (0-15 cm) soil chemical characteristics and classification at Covington, Lake Carl Blackwell, and Tipton, Oklahoma.

Location	pH	NH_4-N	NO_3-N	P	K	Total N	Organic C
		------------------mg kg^{-1}	--------------------			-------------g kg^{-1}	------------
Covington	5.4	10.87	5.17	57	255	1.09	13.3
Classification: Kirkland- Renfrow silt loam (fine, mixed, superactive, thermic Udertic Paleustolls)							
Lake Carl Blackwell	5.3	3	11	12	122	0.68	8.18
Classification: Port-oscar silt loam (fine-silty, mixed, super active, thermic Cumulic Haplustolls)							
Tipton	7.0	4	6	46	284	0.65	6.26
Classification: Tillman-Hollister silt loam (fine-loamy, mixed, thermic, Pachic urgiusoll)							

* pH – 1:1 soil: water, K and P – Mehlich III, Total N and Organic Carbon– dry combustion.

* NH_4 and NO_3-N - 2-M KCL.

Table 4. Field activities, planting dates, seeding rates, Pre-plant nitrogen dates, Foliar nitrogen dates, sensor reading dates, Growing Degree Days, RI_{NDVI}, $RI_{Harvest}$, and harvest dates. (Covington, Lake Carl Blackwell, and Tipton OK, 2002-2004.)

2002-2003	**Covington**	**Lake Carl Blackwell**	**Tipton**
Cultivar	Jagger	Jagger	Custer
Planting date	10-07-02	10-01-02	09-26-02
Seeding rate (kg ha^{-1})	67	90	80
Preplant N date	09-23-02	09-05-02	09-17-02
Topdress N date	02-22-03	02-21&22-03	03-06-03
Rainfall (mm)	443	434	365
Sensing 1 (F 3-4)	01-27-03	01-24-03	01-28-03
GDD	78	84	98
RI_{NDVI}	1.18	1.15	1.45
Sensing 2 (F 4-5)	02-12-03	02-12-03	02-18-03
GDD	85	92	112
RI_{NDVI}	1.24	1.13	1.5
Sensing 3 (F 5-6)	02-22-03	02-20-03	03-06-03
GDD	91	96	119
RI_{NDVI}	1.27	1.14	1.49
Grain harvest date	06-09-03	06-19-03	05-29-03
$RI_{Harvest}$	1.7	1.3	1.5

2003-2004	**Covington**	**Lake Carl Blackwell**	**Tipton**
Cultivar	2174	Jagger	2158
Planting date	09-29-03	10-07-03 10-24-03(re-plant)	09-23-03 (dry planted)
Seeding rate (kg ha^{-1})	78	90	80
Preplant N date	09-17-03	09-10-03	09-09-03
Topdress N date	02-19-04	03-10-04	03-17-04
Effective date			11-07-03
Rainfall (mm)	569	545	331
Sensing 1 (F 2-3)	12-08-03	01-05-04	12-16-03
GDD	60	54	74
RI_{NDVI}	1.47	1.10	0.92
Sensing 2 (F 3-4)	01-15-04	02-19-04	02-18-04
GDD	77	68	106
RI_{NDVI}	2.19	1.10	1.09
Sensing 3 (F 4-5)	02-12-04	02-25-04	03-11-04
GDD	82	72	127
RI_{NDVI}	2.18	1.11	1.49
Sensing 4 (F 5-6)	02-18-04	03-09-04	NA
GDD	83	84	NA
RI_{NDVI}	2.02	1.24	NA
Sensing 5 (F 9)	03-09-04	03-18-04	NA
GDD	100	93	NA
RI_{NDVI}	1.9	1.22	NA
Grain harvest date	06-13-04	6-14-04	05-27-04
$RI_{Harvest}$	1.9	1.24	1.68

* Covington had 18-46-0 @ 56 kg ha^{-1} banded with seed (2002).

* Covington had 11-52-0 @ 50 kg ha^{-1} banded with seed (2003).

* Lake Carl Blackwell had 0-46-0 @45 kg ha^{-1} preplant incorporated (2003 and 2004)

* F =Feekes growth stages, determined by (Large 1954)

* GDD = Growing Degree Days: T_{max}+ T_{min}/2- 4.4° C.

Table 5. NDVI and CV readings for all three sites, Covington, Lake Carl Blackwell, and Tipton, 2003.

	Covington		**Lake Carl Blackwell**		**Tipton**	
Treatment	NDVI	CV	NDVI	CV	NDVI	CV
1	0.4381	23	0.6561	9	0.4026	12
2	0.4629	24	0.6515	8	0.3511	13
3	0.4693	24	0.6122	10	0.3653	13
4	0.4514	23	0.6363	9	0.3714	13
5	0.4821	23	0.6253	9	0.3911	15
6	0.5049	21	0.7033	9	0.4941	14
7	0.5186	21	0.7379	7	0.4829	14
8	0.5048	22	0.7076	8	0.5413	14
9	0.4990	22	0.6949	9	0.4889	16
10	0.5148	22	0.7009	9	0.5077	13
11	0.5543	20	0.7459	7	0.5968	12
12	0.5409	20	0.7265	8	0.6141	13
13	0.5377	21	0.7316	7	0.5905	13
14	0.5287	22	0.7339	8	0.6414	13
15	0.5213	22	0.7449	6	0.6008	15

Table 6. NDVI and CV readings for all three sites, Covington, Lake Carl Blackwell, and Tipton, 2004

	Covington		**Lake Carl Blackwell**		**Tipton**	
Treatment	NDVI	CV	NDVI	CV	NDVI	CV
1	0.377	18	0.5059	18	0.6544	7
2	0.4157	16	0.5110	19	0.5628	10
3	0.4016	18	0.5036	19	0.5420	11
4	0.4194	19	0.5146	18	0.6339	8
5	0.4396	16	0.5074	20	0.7326	7
6	0.5115	21	0.5157	19	0.8116	8
7	0.5036	20	0.5097	18	0.8047	6
8	0.4858	18	0.5542	17	0.8266	6
9	0.5356	18	0.5249	18	0.8068	7
10	0.5089	20	0.5705	14	0.7769	7
11	0.6044	15	0.5821	16	0.8498	7
12	0.5647	18	0.5593	18	0.8645	4
13	0.5836	19	0.6130	15	0.8548	5
14	0.5774	18	0.5535	17	0.8733	5
15	0.6306	15	0.5608	16	0.8890	2

Table 7 Treatment, preplant N, topdress N RI factor, topdress N applied, total N applied, yield, grain N uptake, and % NUE, for Covington, 2003.

Treatment	Preplant N	Topdress N RI	Topdress N Applied	Total N Applied	Grain Yield	Grain N uptake	NUE %	% Of Max Yield†
	--kg ha^{-1}----------------------------------							
1	0	0	0	0	3170	61	--	61
2	0	RI	19	19	4295	85	126	82
3	0	RI * 1.3	48	48	4630	93	67	88
4	0	RI * 1.6	74	74	5122	114	72	98
5	0	RI * 2.0	122	122	5271	130	57	101
6	45	0	0	45	4527	94	73	87
7	45	RI	22	67	4936	104	64	94
8	45	RI * 1.3	54	99	5419	113	53	104
9	45	RI * 1.6	86	121	5215	122	50	100
10	45	RI * 2.0	134	179	5875	146	47	112
11	90	0	0	90	5234	125	71	100
12	90	RI	23	113	5225	117	49	100
13	90	RI * 1.3	60	150	5708	140	53	109
14	90	RI * 1.6	94	184	5569	136	41	106
15	90	RI * 2.0	138	228	5522	146	37	106
RI$_{NDVI}$					1.27			
RI$_{Harvest}$					1.7			
SED					219	9	10	

† Plot yield (kg ha^{-1}) divided by yield (kg ha^{-1}) from treatment 11

Table 8. Treatment, preplant N, topdress N RI factor, topdress N applied, total N applied, yield, grain N uptake, and % NUE, for Lake Carl Blackwell, 2003.

Treatment	Preplant N	Topdress N RI	Topdress N Applied	Total N Applied	Grain Yield	Grain N uptake	NUE %	% Of Max Yield†
	--kg ha^{-1}----------------------------------							
1	0	0	0	0	3207	58	--	75
2	0	RI	19	19	3570	68	53	83
3	0	RI * 1.3	58	58	3802	84	45	89
4	0	RI * 1.6	104	104	4453	102	42	104
5	0	RI * 2.0	141	141	4453	119	43	104
6	45	0	0	45	3579	70	27	84
7	45	RI	23	68	4527	90	47	106
8	45	RI * 1.3	75	120	4360	100	35	102
9	45	RI * 1.6	120	165	4472	108	30	105
10	45	RI * 2.0	139	184	4546	127	38	106
11	90	0	0	90	4276	105	52	100
12	90	RI	23	113	4230	94	32	99
13	90	RI * 1.3	80	170	4341	114	33	102
14	90	RI * 1.6	117	207	4406	119	30	103
15	90	RI * 2.0	120	210	4537	117	28	106
RI$_{NDVI}$					1.14			
RI$_{Harvest}$					1.3			
SED					313	10	14	

† Plot yield (kg ha^{-1}) divided by yield (kg ha^{-1}) from treatment 11

Table 9. Treatment, preplant N, topdress N RI factor, topdress N applied, total N applied, yield, grain N uptake, and % NUE, for Tipton, 2003.

Treatment	Preplant N	Topdress N RI	Topdress N Applied	Total N Applied	Grain Yield	Grain N uptake	NUE %	% Of Max Yield†
	---------------------------------------	----------------------kg ha^{-1}	----------------------	---------------------------------	---------------------------------	---------------------------------		
1	0	0	0	0	1357	29	--	65
2	0	RI	22	22	1311	27	--	63
3	0	RI * 1.3	45	45	1673	35	13	80
4	0	RI * 1.6	66	66	1859	43	21	89
5	0	RI * 2.0	98	98	2278	60	31	109
6	45	0	0	45	1264	27	--	61
7	45	RI	30	75	1673	38	12	80
8	45	RI * 1.3	66	111	2240	56	24	108
9	45	RI * 1.6	86	131	2092	54	19	100
10	45	RI * 2.0	129	174	2612	72	25	125
11	90	0	0	90	2082	50	23	100
12	90	RI	41	131	2612	67	29	125
13	90	RI * 1.3	74	164	2808	75	28	135
14	90	RI * 1.6	123	213	3086	87	27	148
15	90	RI * 2.0	160	250	3031	90	24	146
RI $_{\text{NDVI}}$					1.49			
RI $_{\text{Harvest}}$					1.5			
SED					190	5	7	

† Plot yield (kg ha^{-1}) divided by yield (kg ha^{-1}) from treatment 11

Table 10. Treatment, preplant N, topdress N RI factor, topdress N applied, total N applied, yield, grain N uptake, and % NUE, for Covington, 2004.

Treatment	Preplant N	Topdress N RI	Topdress N Applied	Total N Applied	Grain Yield	Grain N uptake	NUE %	% Of Max Yield†
	---------------------------------------	----------------------kg ha^{-1}	----------------------	---------------------------------	---------------------------------	---------------------------------		
1	0	0	0	0	1985	38	--	53
2	0	RI	86	86	3736	71	38	100
3	0	RI * 1.3	129	129	4000	78	31	107
4	0	RI * 1.6	167	167	4454	92	32	119
5	0	RI * 2.0	186	186	4831	104	35	129
6	45	0	0	45	2846	54	36	76
7	45	RI	108	153	4391	90	34	117
8	45	RI * 1.3	163	208	4494	96	28	120
9	45	RI * 1.6	150	195	4598	102	33	123
10	45	RI * 2.0	163	208	4699	109	34	125
11	90	0	0	90	3751	81	48	100
12	90	RI	138	228	4765	112	33	127
13	90	RI * 1.3	127	217	4601	108	32	123
14	90	RI * 1.6	130	220	4760	111	33	127
15	90	RI * 2.0	98	188	4551	98	32	121
RI $_{\text{NDVI}}$					2.02			
RI $_{\text{Harvest}}$					1.89			
SED					254	7	3	

† Plot yield (kg ha^{-1}) divided by yield (kg ha^{-1}) from treatment 11

Table 11. Treatment, preplant N, topdress N RI factor, topdress N applied, total N applied, yield, grain N uptake, and % NUE, for Lake Carl Blackwell, 2004.

Treatment	Preplant N	Topdress N RI	Topdress N Applied	Total N Applied	Grain Yield	Grain N uptake	NUE %	% Of Max Yield†
	---kg ha^{-1}---							
1	0	0	0	0	3047	46	--	81
2	0	RI	37	37	3507	61	41	93
3	0	RI * 1.3	78	78	3675	75	37	98
4	0	RI * 1.6	104	104	3552	79	32	94
5	0	RI * 2.0	145	145	3533	82	25	94
6	45	0	0	45	3502	68	49	93
7	45	RI	39	84	3760	71	30	100
8	45	RI * 1.3	88	133	3556	89	32	94
9	45	RI * 1.6	116	161	3505	90	27	93
10	45	RI * 2.0	127	172	3355	92	27	89
11	90	0	0	90	3766	78	36	100
12	90	RI	47	137	3649	89	31	97
13	90	RI * 1.3	89	179	3339	82	20	89
14	90	RI * 1.6	113	203	3471	93	23	92
15	90	RI * 2.0	122	212	3542	92	22	94
RI $_{\text{NDVI}}$					1.24			
RI $_{\text{Harvest}}$					1.24			
SED					137	6	8	

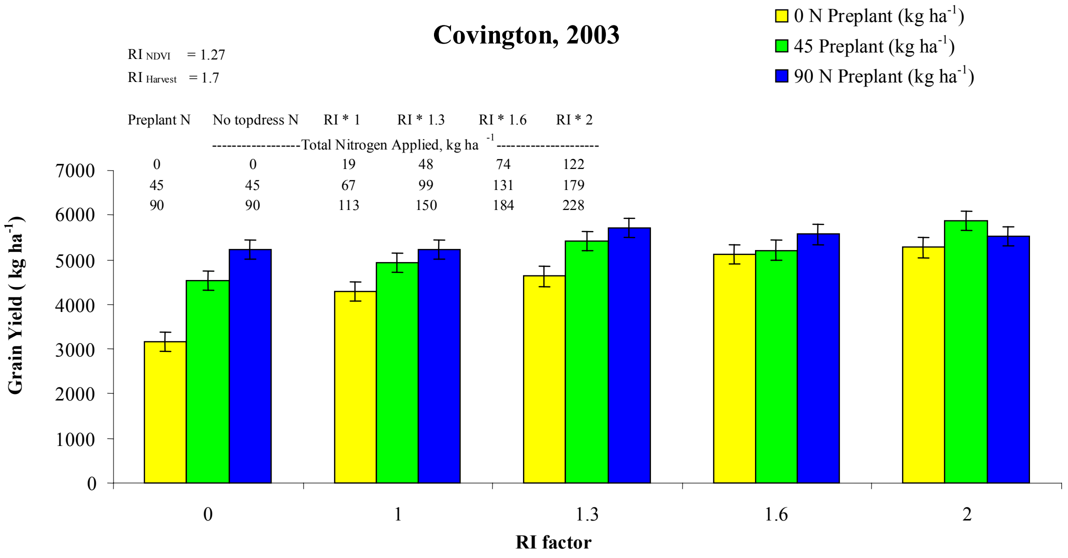
† Plot yield (kg ha^{-1}) divided by yield (kg ha^{-1}) from treatment 11

Table 12. Treatment, preplant N, topdress N RI factor, topdress N applied, total N applied, yield, grain N uptake, and % NUE, for Tipton, 2004.

Treatment	Preplant N	Topdress N RI	Topdress N Applied	Total N Applied	Grain Yield	Grain N uptake	NUE %	% Of Max Yield†
	---kg ha^{-1}---							
1	0	0	0	0	2329	32	--	60
2	0	RI	48	48	3605	54	46	92
3	0	RI * 1.3	75	75	3739	63	41	96
4	0	RI * 1.6	140	140	4394	92	43	112
5	0	RI * 2.0	173	173	4657	106	43	119
6	45	0	0	45	3533	50	40	90
7	45	RI	97	142	4625	94	44	118
8	45	RI * 1.3	148	193	4845	108	39	124
9	45	RI * 1.6	151	196	4189	91	30	107
10	45	RI * 2.0	142	187	4100	94	33	105
11	90	0	0	90	3909	66	38	100
12	90	RI	120	210	4196	97	31	107
13	90	RI * 1.3	140	230	4275	98	29	109
14	90	RI * 1.6	134	224	4228	90	26	108
15	90	RI * 2.0	129	219	4154	95	29	106
RI $_{\text{NDVI}}$					1.49			
RI $_{\text{Harvest}}$					1.68			
SED					260	5	4	

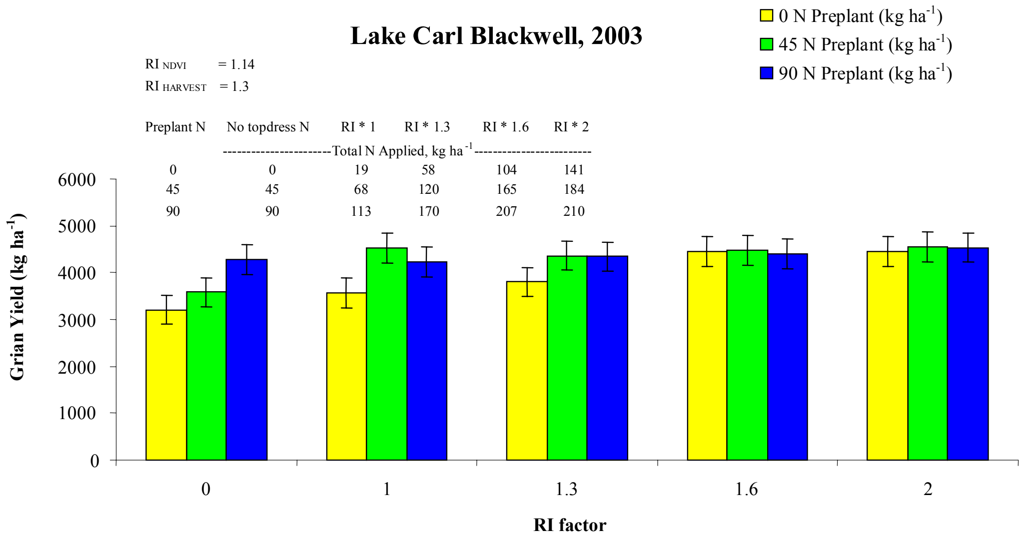
† Plot yield (kg ha^{-1}) divided by yield (kg ha^{-1}) from treatment 11

Appendix



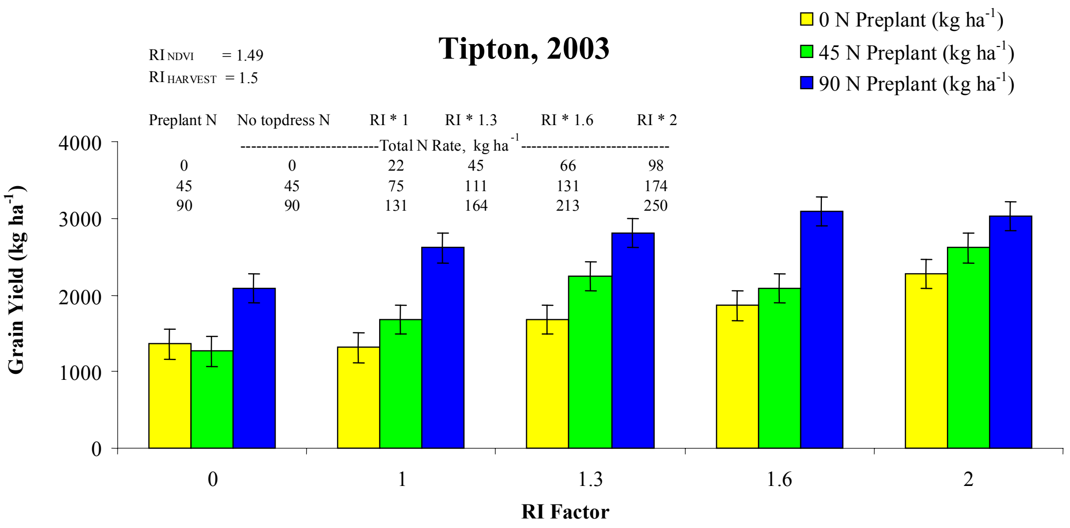
* Error bars indicate the SED for this site (kg ha^{-1}).
* SED-Standard error of the difference between two equally replicated means
* SED = 219

Figure 1 Wheat grain yield (kg ha^{-1}) influenced by preplant nitrogen and topdress nitrogen, determined as a function of response index; Covington, 2003.



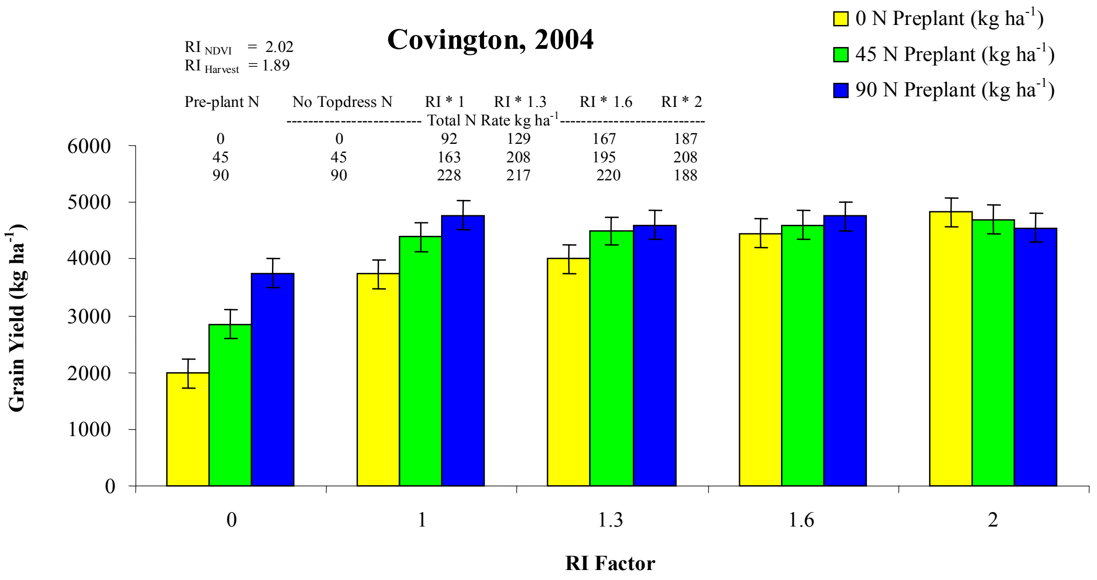
* Error bars indicate SED for this site, (kg ha^{-1}).
* SED-Standard error of the difference between two equally replicated means.
* SED = 313

Figure 2. Wheat grain yield (kg ha^{-1}) influenced by preplant nitrogen and topdress nitrogen, determined as a function of response index; Lake Carl Blackwell, 2003.



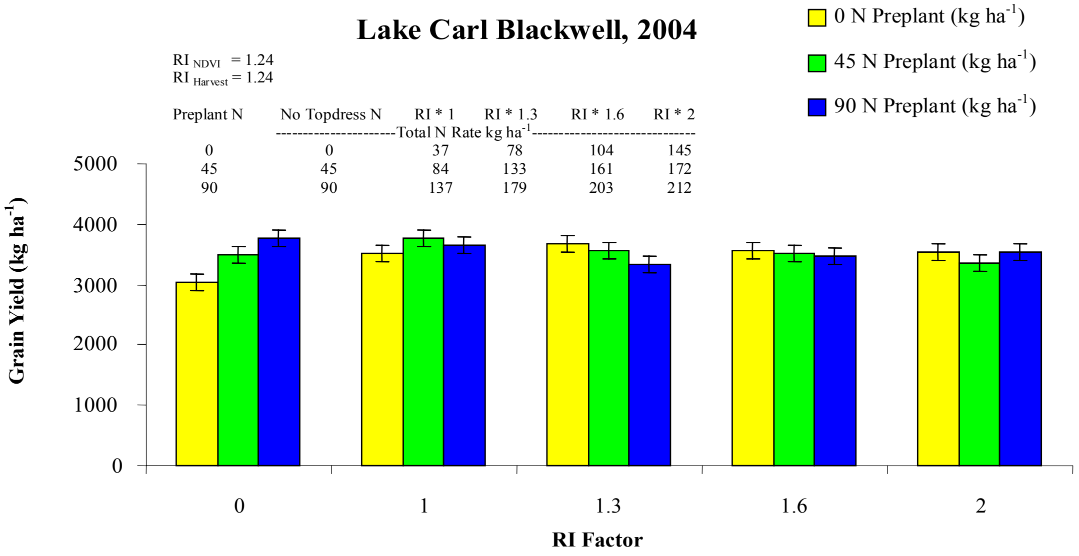
* Error bars indicate SED for this site, (kg ha^{-1}).
* SED-Standard error of the difference between two equally replicated means.
* SED = 190

Figure 3. Wheat grain yield (kg ha^{-1}) influenced by preplant nitrogen and topdress nitrogen, determined as a function of response index; Tipton, 2003.



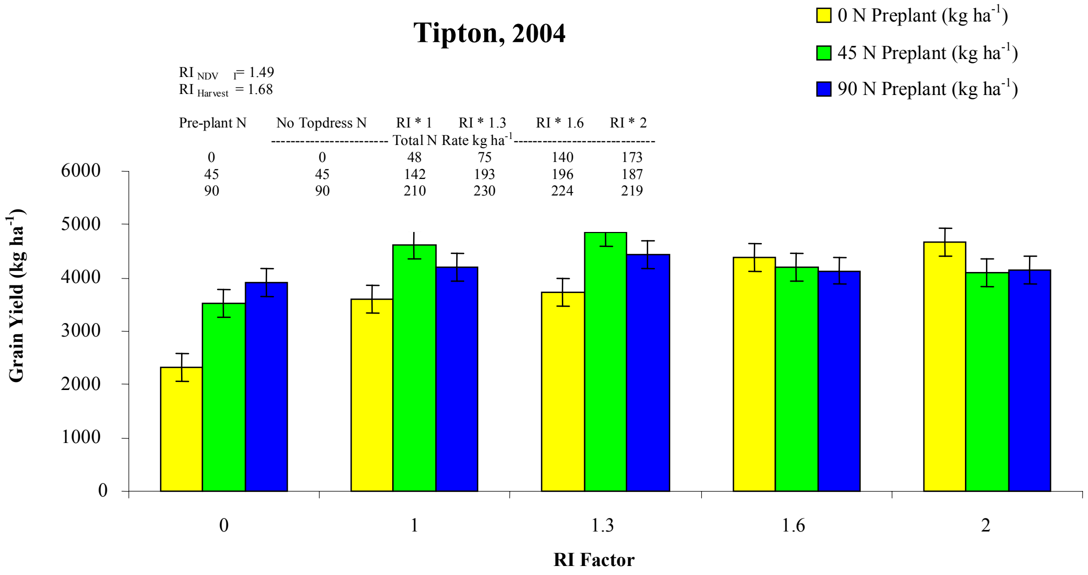
* Error bars indicate the SED for this site (kg ha^{-1}).
* SED-Standard error of the difference between two equally replicated means.
* SED = 254

Figure 4. Wheat grain yield (kg ha^{-1}) influenced by preplant nitrogen and topdress nitrogen, determined as a function of response index; Covington, 2004.



* Error bars indicate the SED for this site (kg ha^{-1}).
* SED-Standard error of the difference between two equally replicated means.
* SED = 137

Figure 5. Wheat grain yield (kg ha^{-1}) influenced by preplant nitrogen and topdress nitrogen, determined as a function of response index; Lake Carl Blackwell, 2004.



* Error bars indicate the SED for this site (kg ha^{-1}).
* SED-Standard error of the difference between two equally replicated means.
* SED = 260

Figure 6. Wheat grain yield (kg ha^{-1}) influenced by preplant nitrogen and topdress nitrogen, determined as a function of response index; Tipton, 2004.

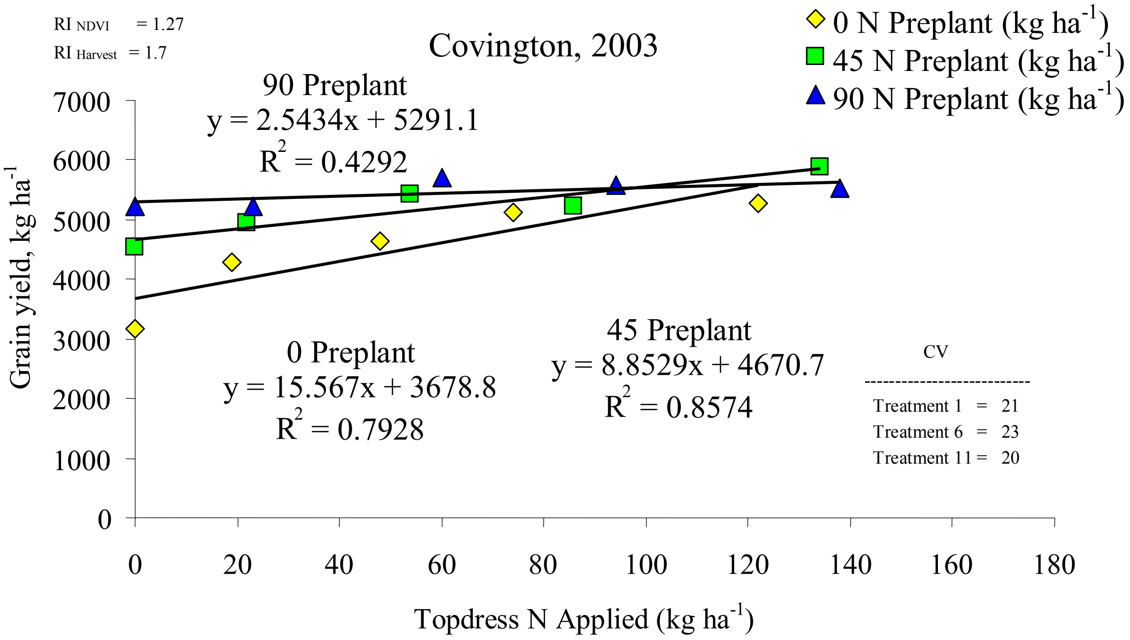


Figure 7. Grain Yield versus Topdress N Rate, Covington 2003

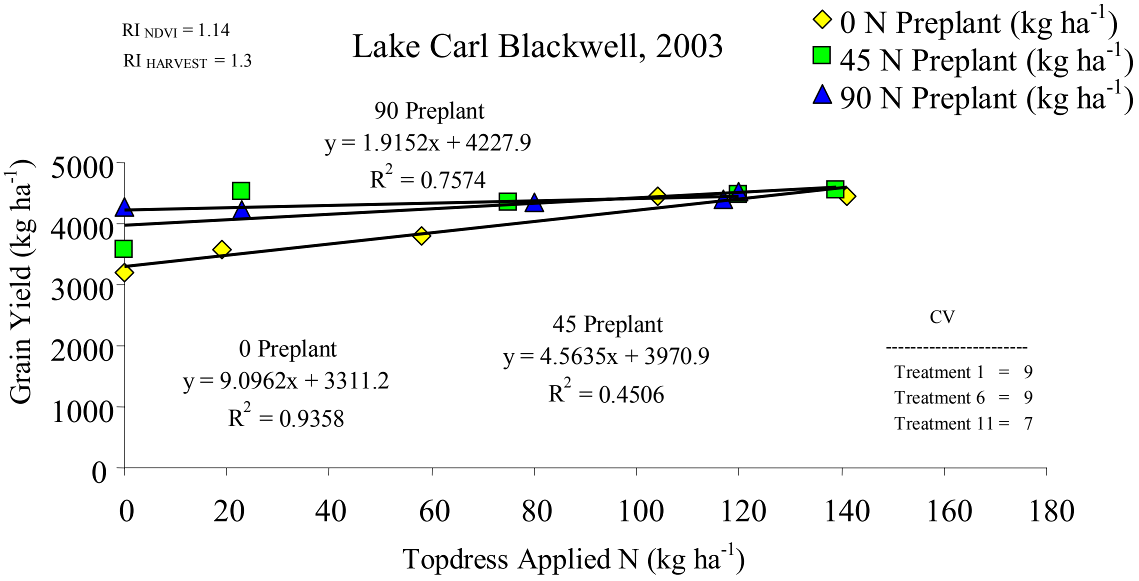


Figure 8. Grain Yield versus Topdress N Rate, Lake Carl Blackwell 2003

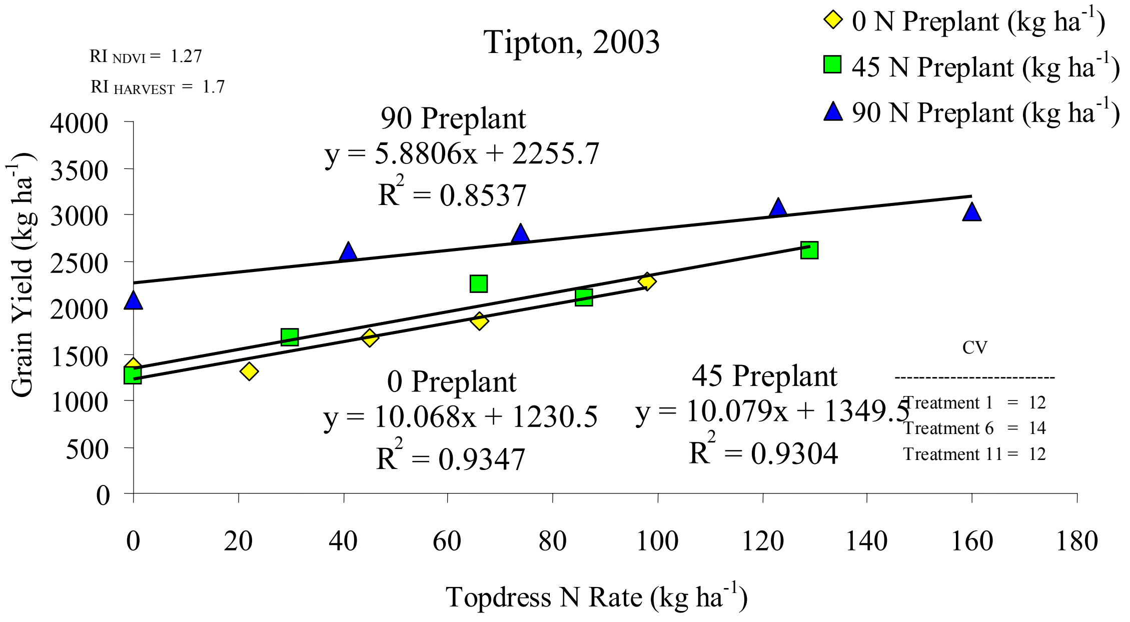


Figure 9. Grain Yield versus Topdress N Rate, Tipton 2003

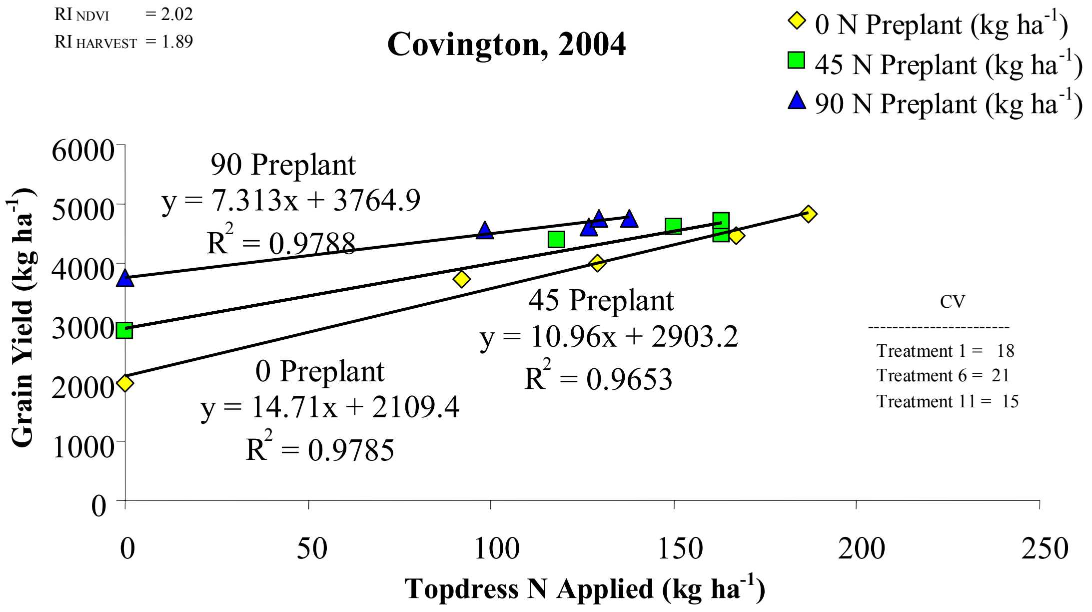


Figure 10. Grain Yield versus Topdress N Rate, Covington 2004

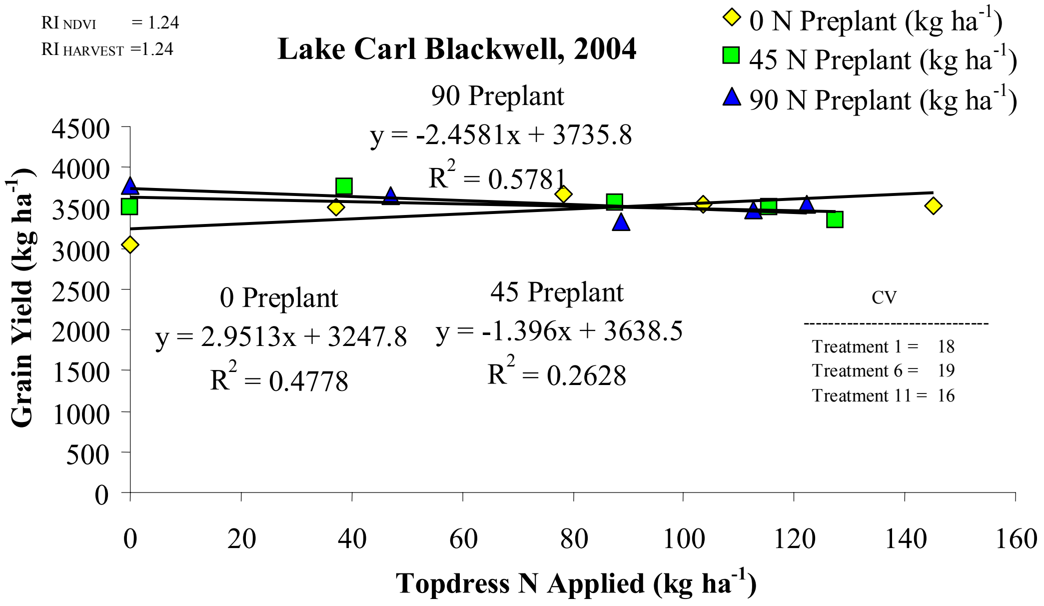


Figure 11. Grain Yield versus Topdress N Rate, Lake Carl Blackwell 2004

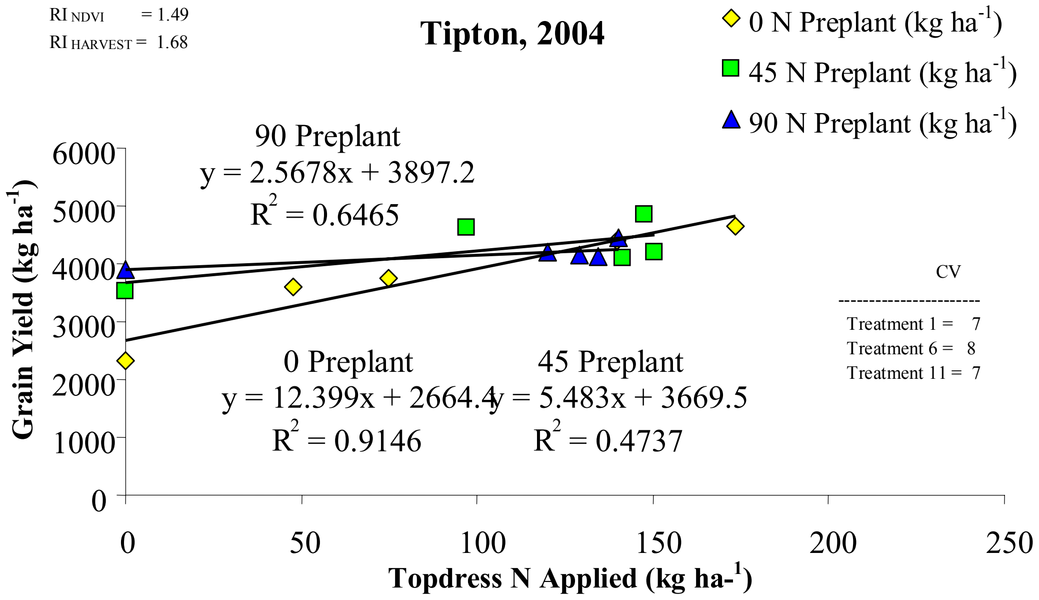
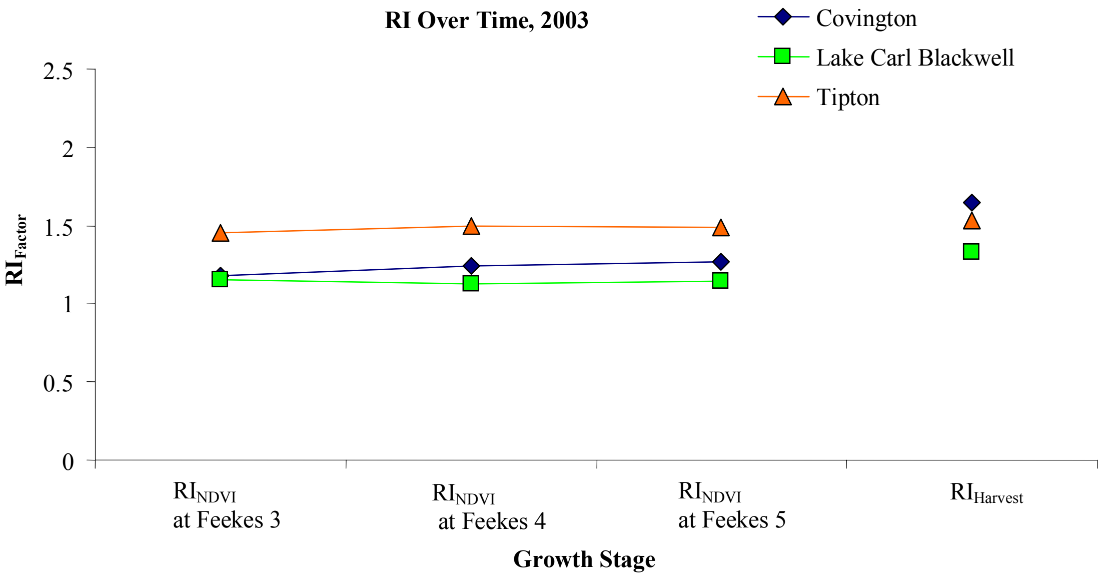
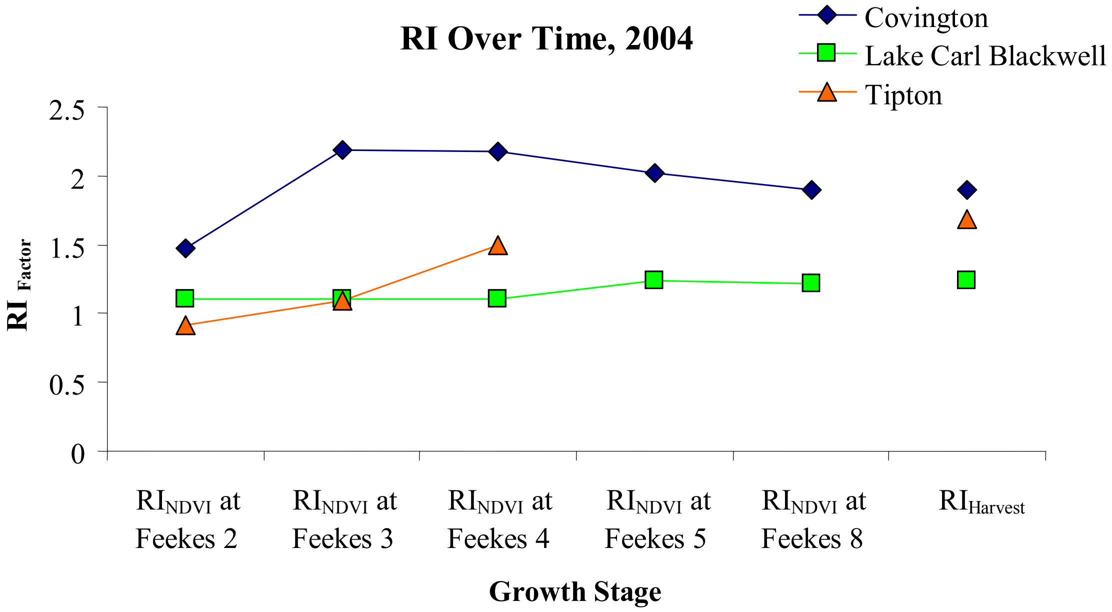


Figure 12. Grain Yield versus Topdress N Rate, Tipton 2004



*Response index NDVI (RI_{NDVI}), is computed by dividing the mid-season NDVI measurement from the non-N limiting plot divided by the common farmer practice where less N is applied preplant.
*Response index Harvest ($RI_{Harvest}$), is computed by dividing the mean grain yield of the non-N limiting plot divided by the common farmer practice where less N is applied preplant.

Figure 13. Response Index observed over time for all three locations. Covington, Lake Carl Blackwell, and Tipton, 2003.



*Response index NDVI (RI_{NDVI}), is computed by dividing the mid-season NDVI measurement from the non-N limiting plot divided by the common farmer practice where less N is applied preplant.
*Response index Harvest ($RI_{Harvest}$), is computed by dividing the mean grain yield of the non-N limiting plot divided by the common farmer practice where less N is applied preplant.

Figure 14. Response Index observed over time for all three locations, Covington, Lake Carl Blackwell, and Tipton, 2004.

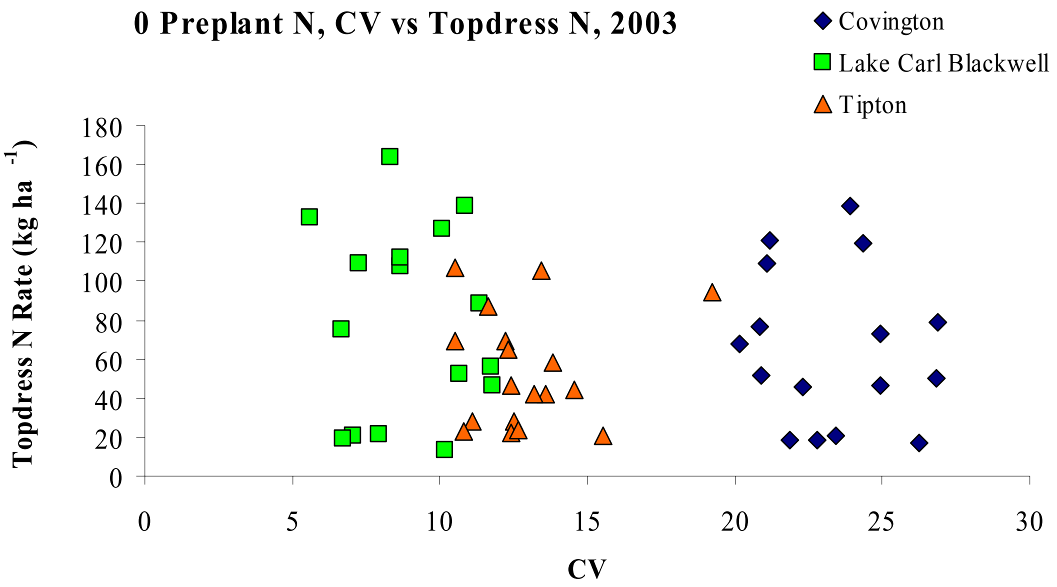


Figure 15. Coefficient of Variation (CV) versus topdress N rate at 0 preplant N, Covington, Lake Carl Blackwell, Tipton 2003.

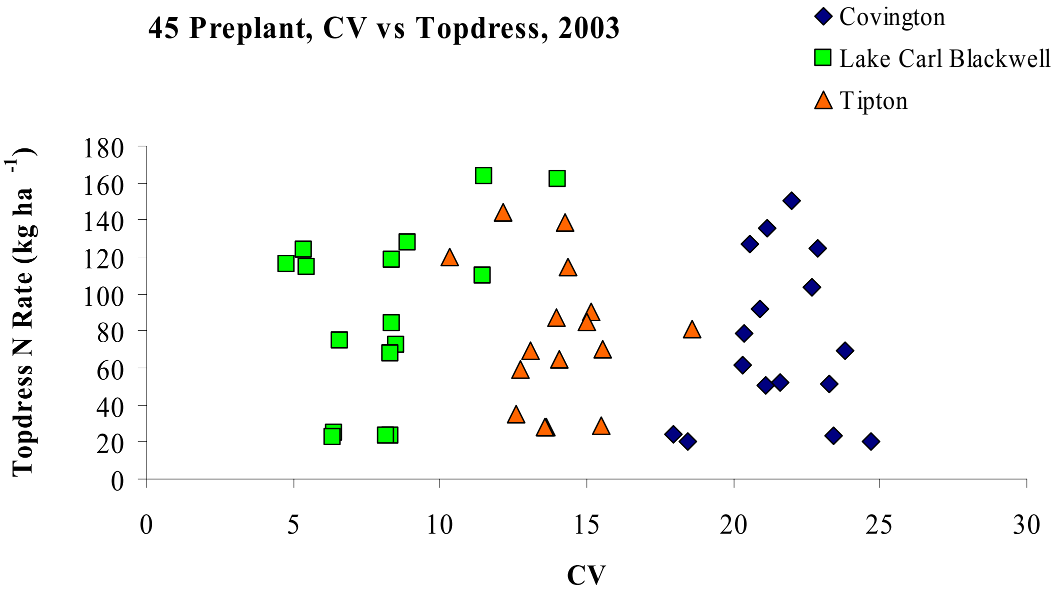


Figure 16. Coefficient of Variation (CV) versus topdress N rate at 45 preplant N, Covington, Lake Carl Blackwell, and Tipton 2003.

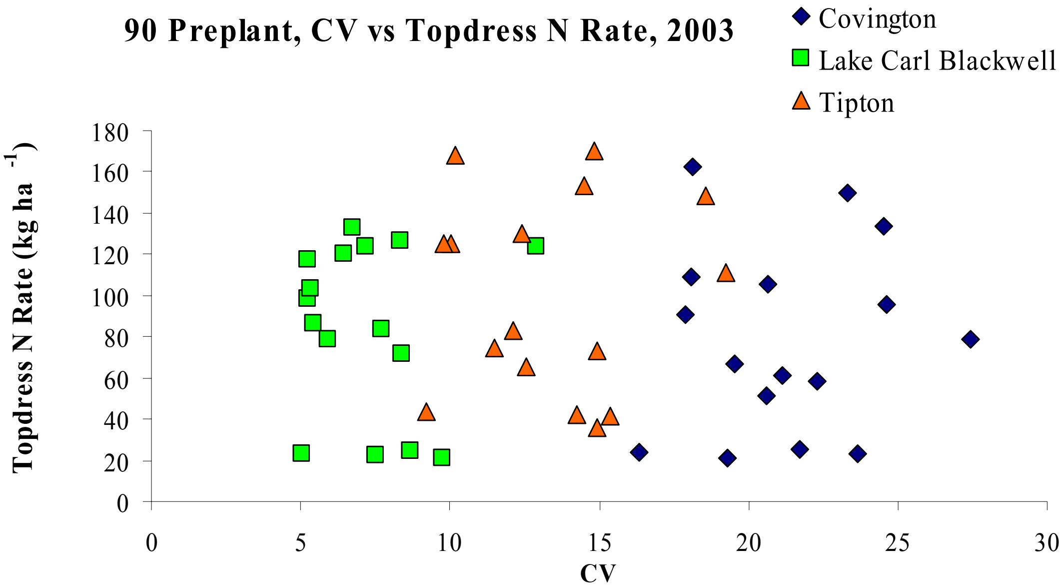


Figure 17. Coefficient of Variation (CV) versus topdress N rate at 90 preplant N, Covington, Lake Carl Blackwell, and Tipton, 2003.

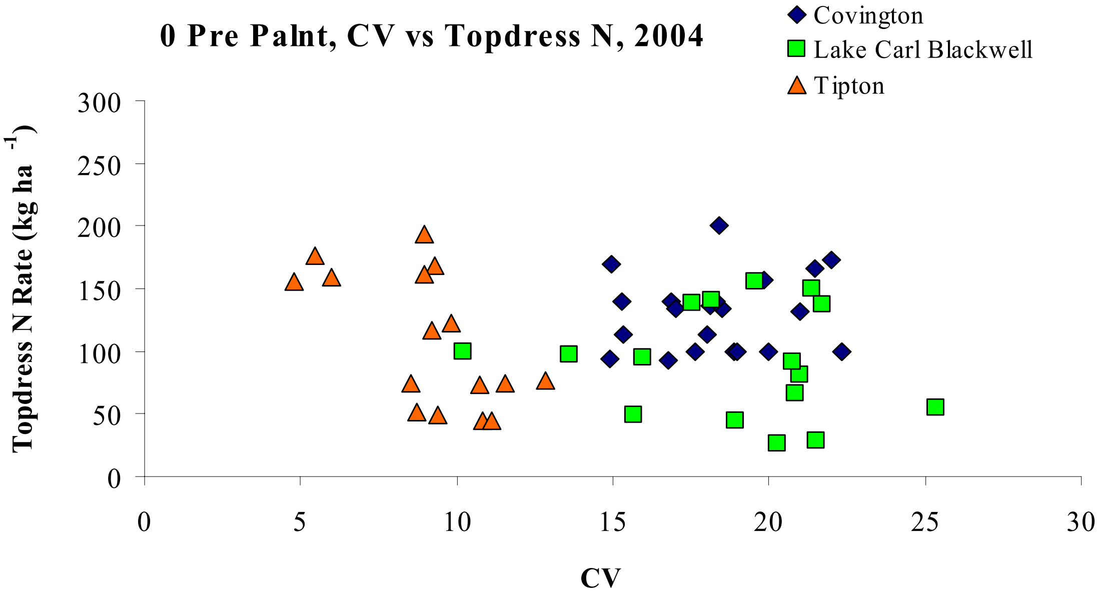


Figure 18. Coefficient of Variation (CV) versus topdress N rate at 0 preplant N, Covington, Lake Carl Blackwell, and Tipton 2004.

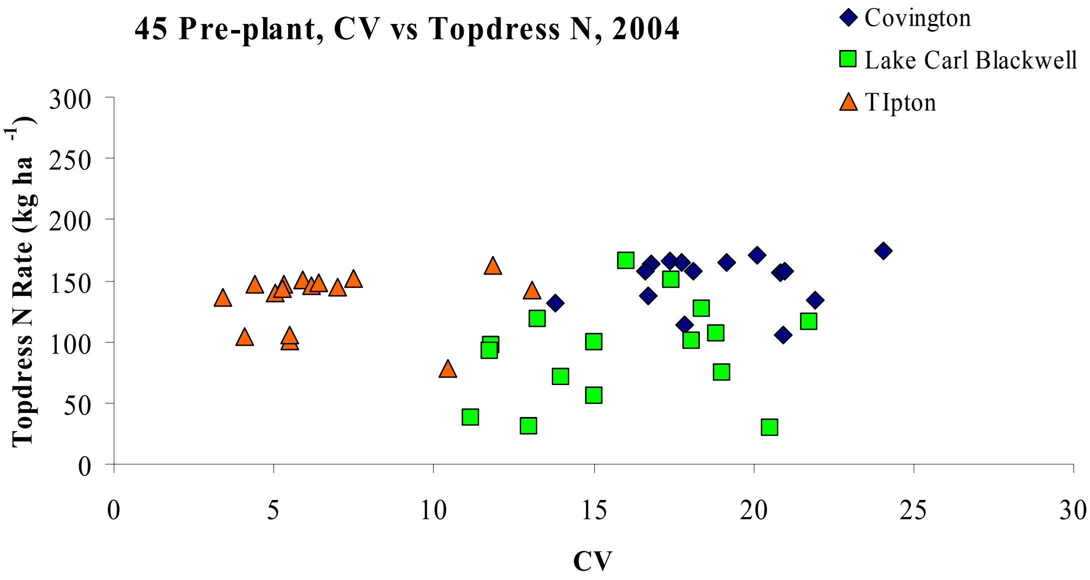


Figure 19. Coefficient of Variation (CV) versus topdress N rate at 45 preplant N, Covington, Lake Carl Blackwell, and Tipton, 2004.

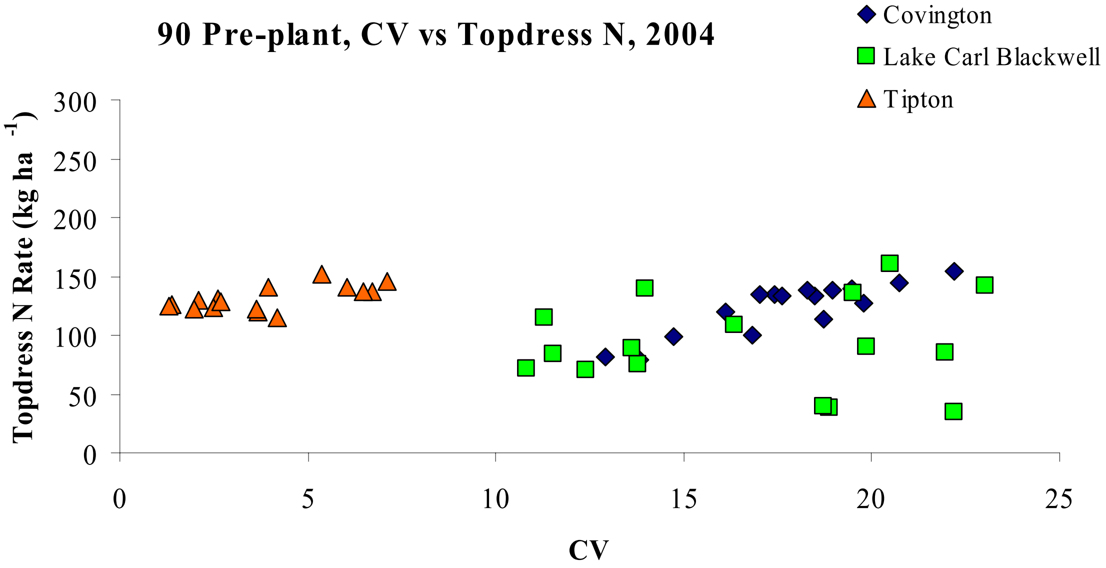
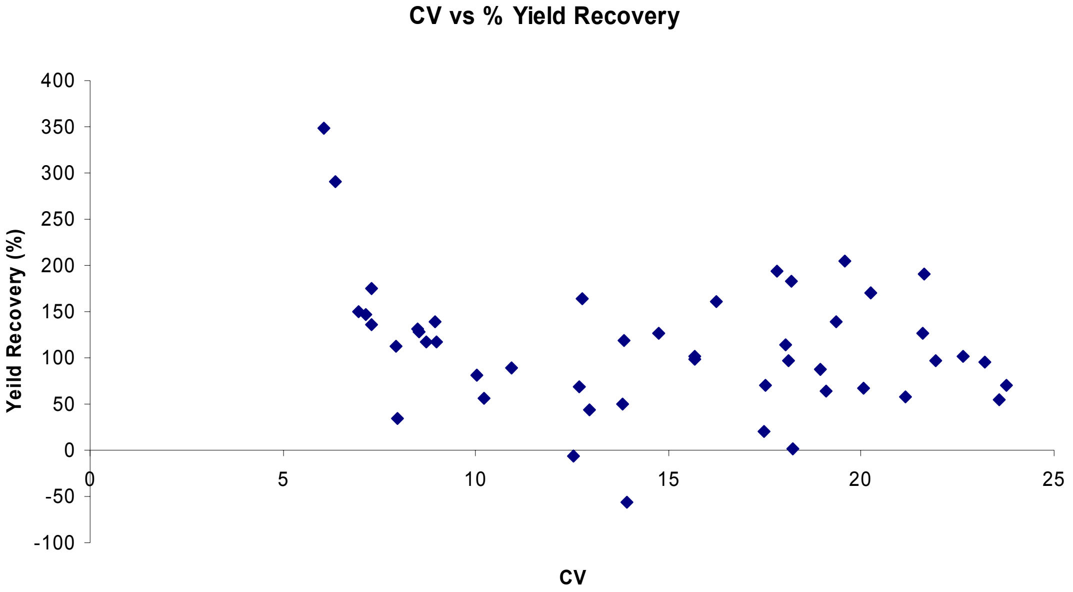


Figure 20. Coefficient of Variation (CV) versus topdress N rate at 90 preplant N, Covington, Lake Carl Blackwell, and Tipton, 2004.



Figur 21. CV vs Yield Recovery (%) in all Locations Both Years (2003-2004).

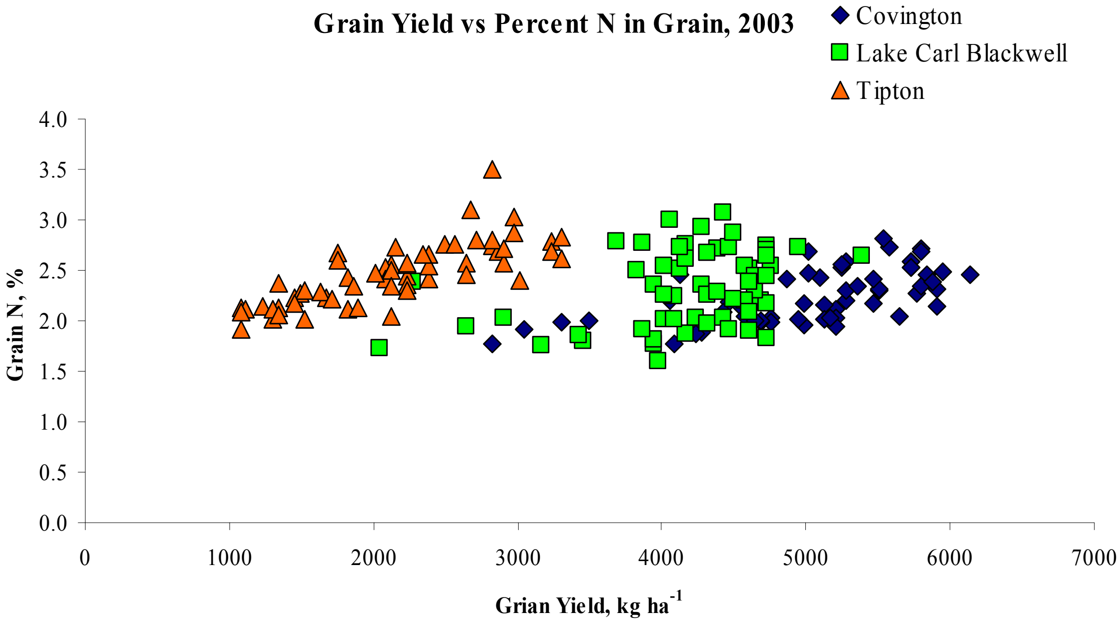


Figure 22. Grain Yield kg ha^{-1} versus % Grain N at Covington, Lake Carl Blackwell, and Tipton, 2003

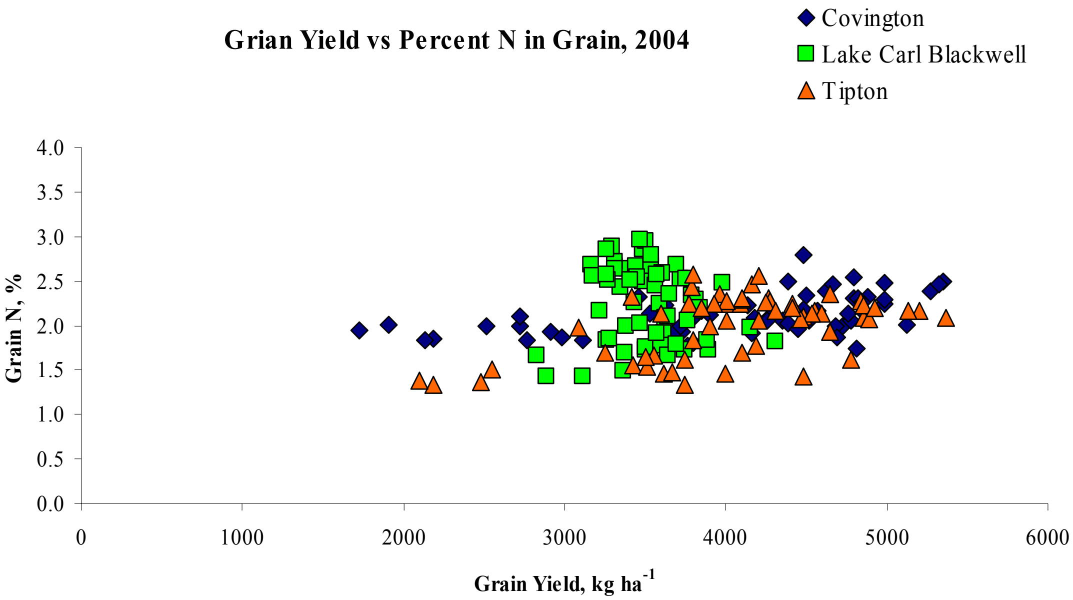


Figure 23. Grain Yield kg ha^{-1} versus % Grain N at Covington, Lake Carl Blackwell, and Tipton, 2004

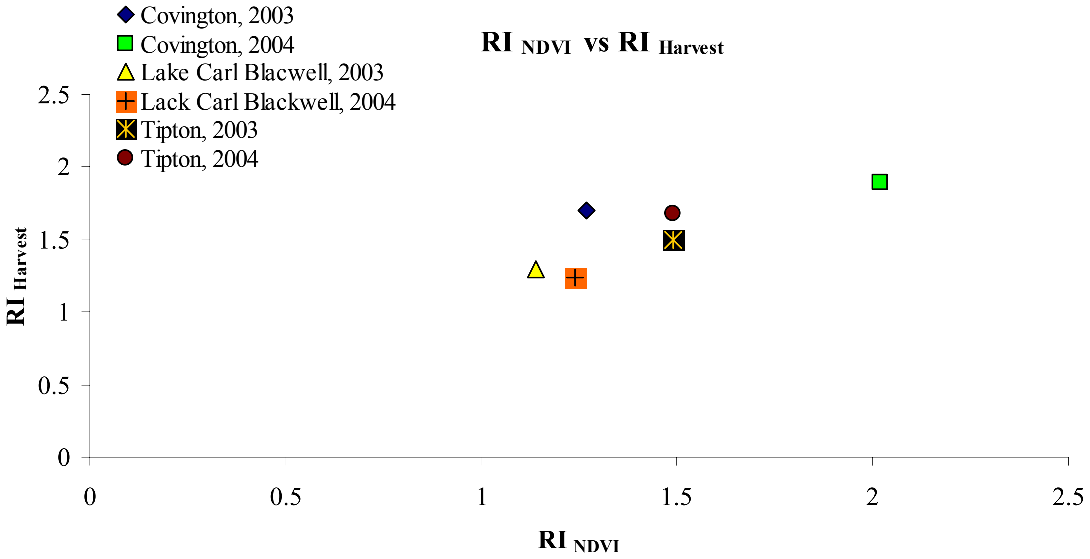


Figure 24. RI $_{NDVI}$ vs RI $_{Harvest}$ using 0 and 90 Preplant NDVI's and Harvest numbers for 2003-2004 all sites. (Covington, Lake Carl Blackwell, and Tipton).

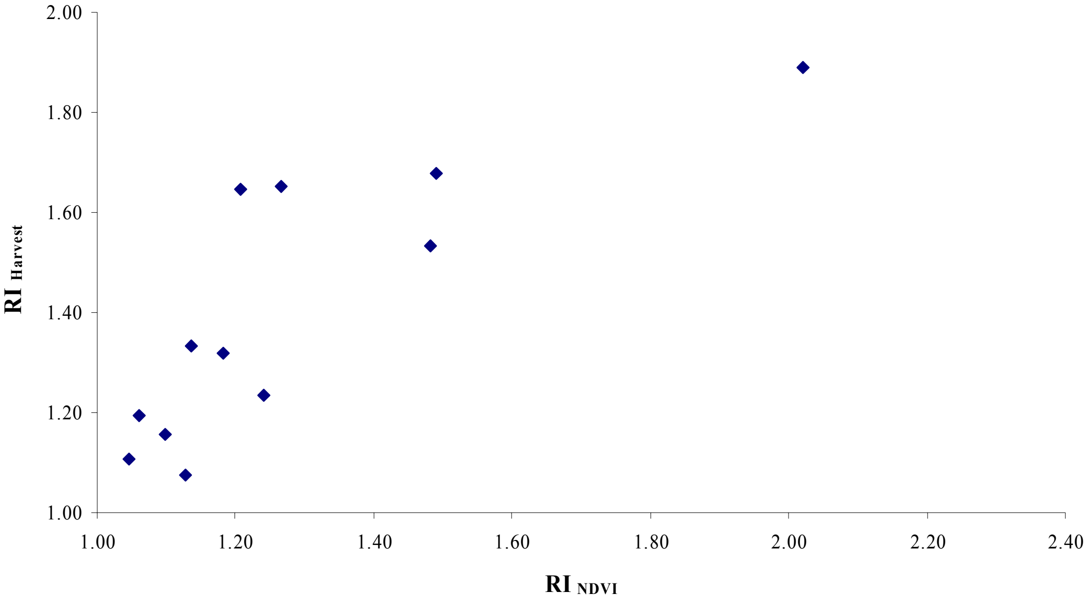


Figure 25. RI_{NDVI} vs $RI_{Harvest}$ using 0, 45 and 90 Preplant NDVI and Harvest for 2002-2004 all Locations Both Years (Covington, Lake Carl Blackwell, and Tipton)

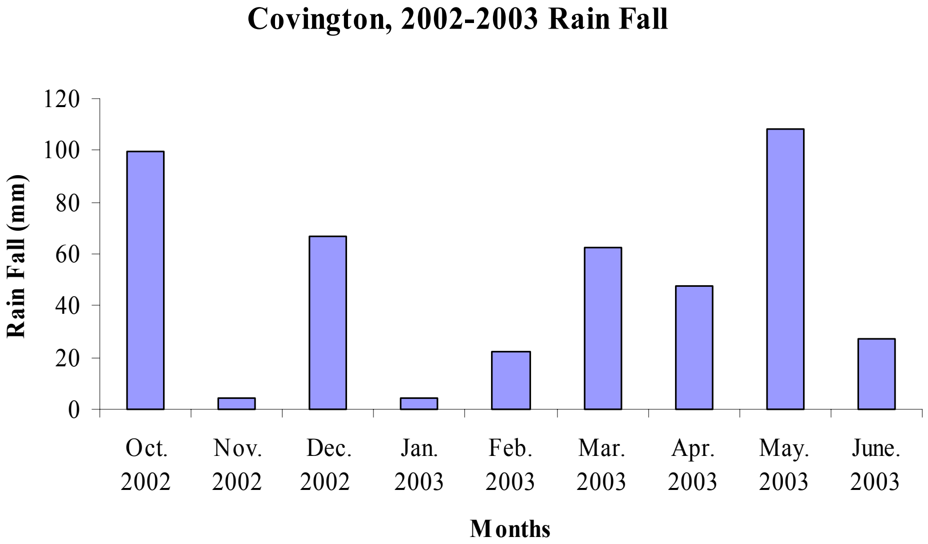


Figure 26. Rainfall data for 2002-2003 growing season, Covington.

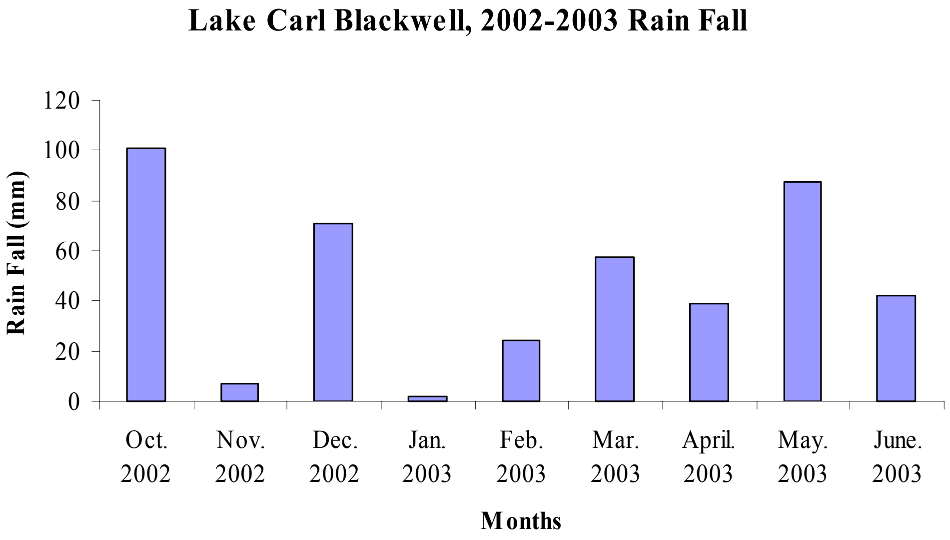


Figure 27. Rainfall data for 2002-2003 growing season, Lake Carl Blackwell

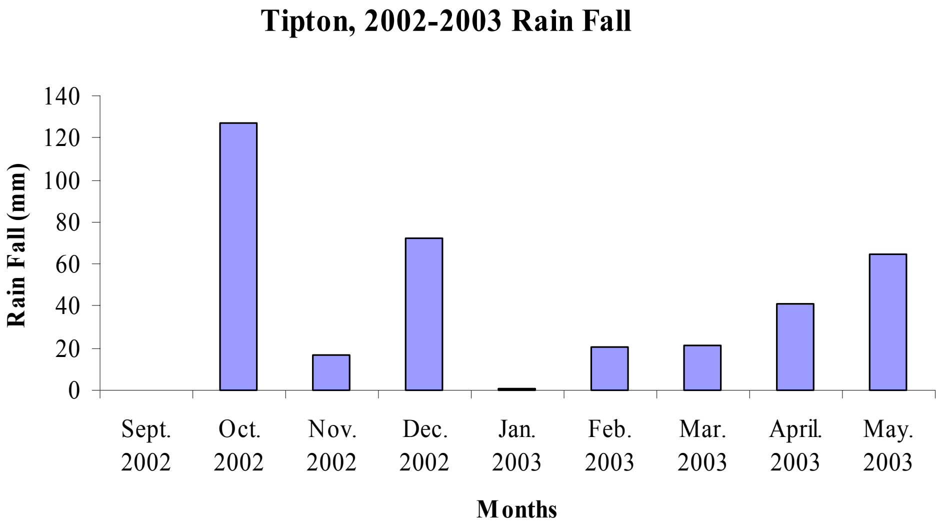


Figure 28. Rainfall data for 2002-2003 growing season, Tipton

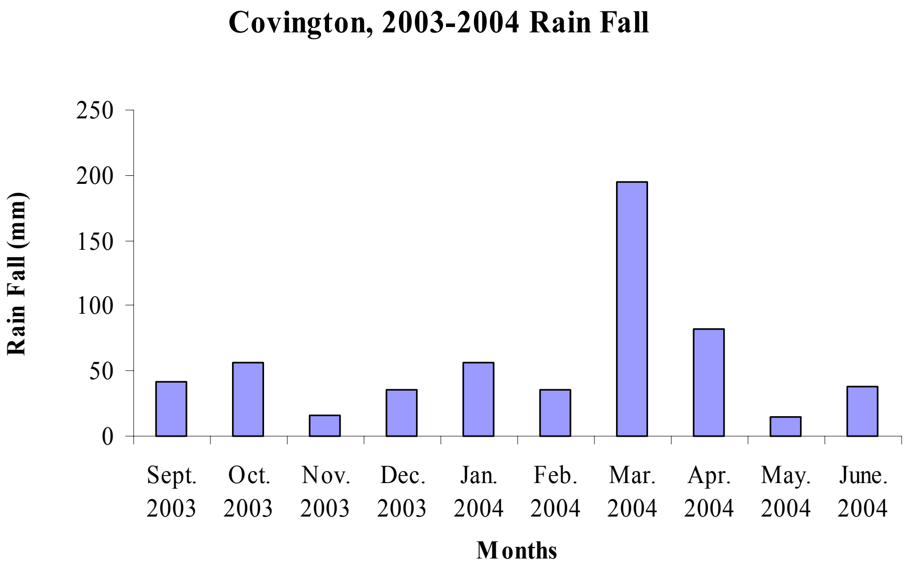


Figure 29. Rainfall data for 2003-2004 growing season, Covington

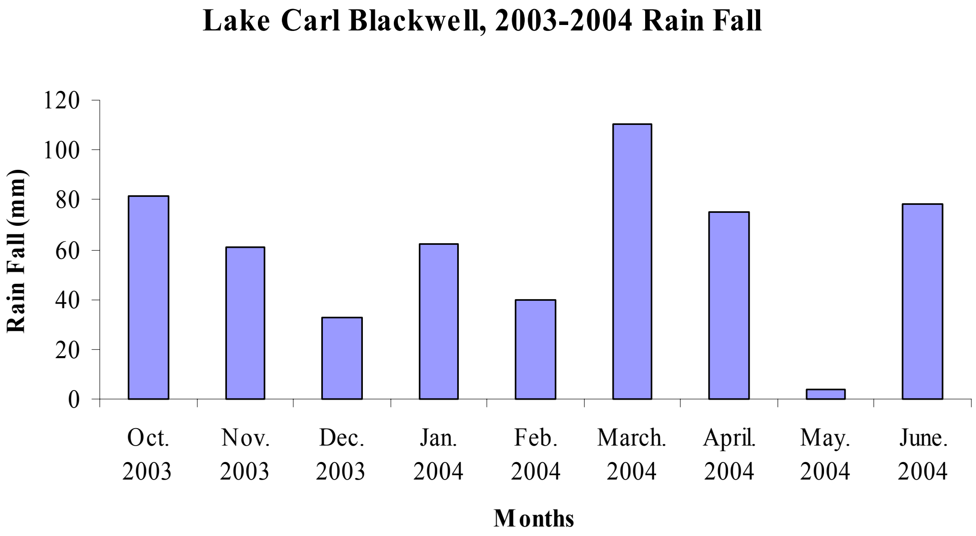


Figure 30. Rainfall data for 2003-2004 growing season, Lake Carl Blackwell

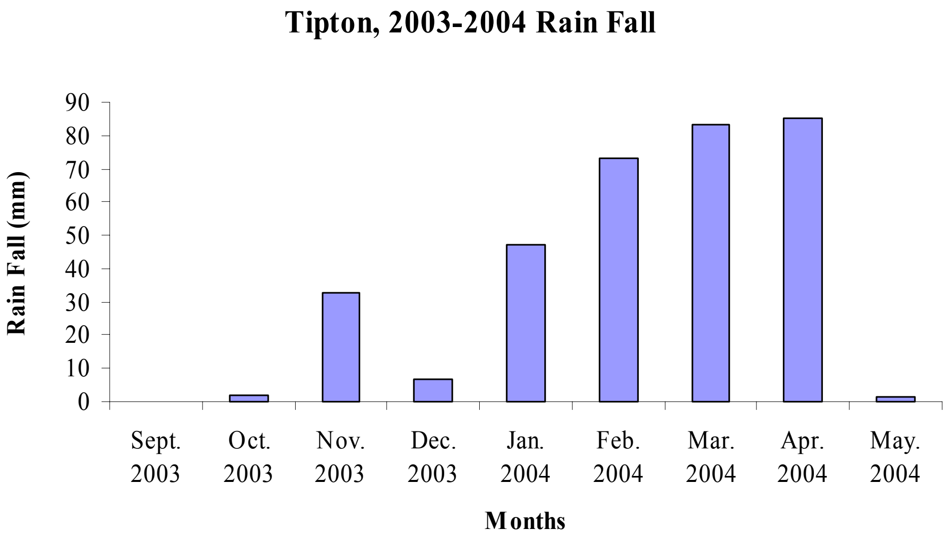


Figure 31. Rainfall data for 2003-2004 growing season, Tipton

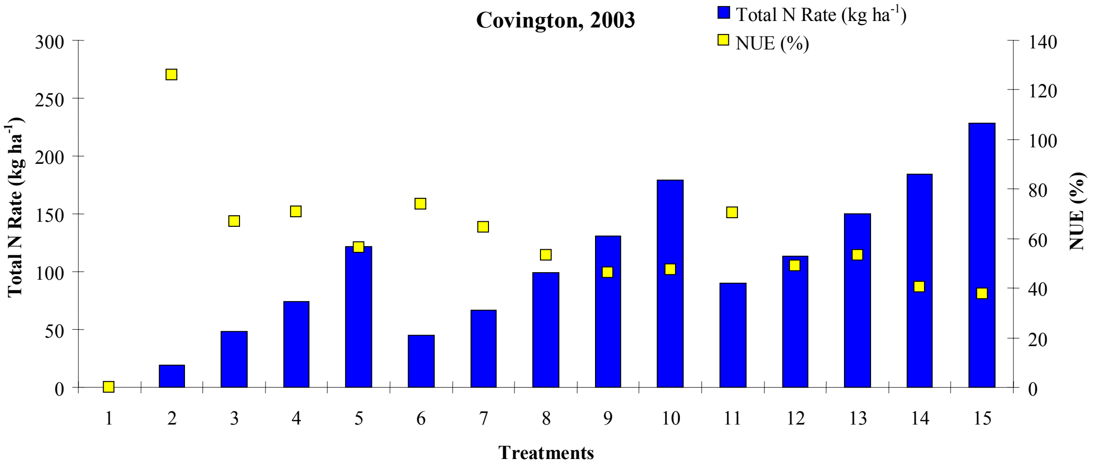


Figure 32. Treatments in respect to Total N Rate (kg ha^{-1}) and NUE (%), Covington, 2003

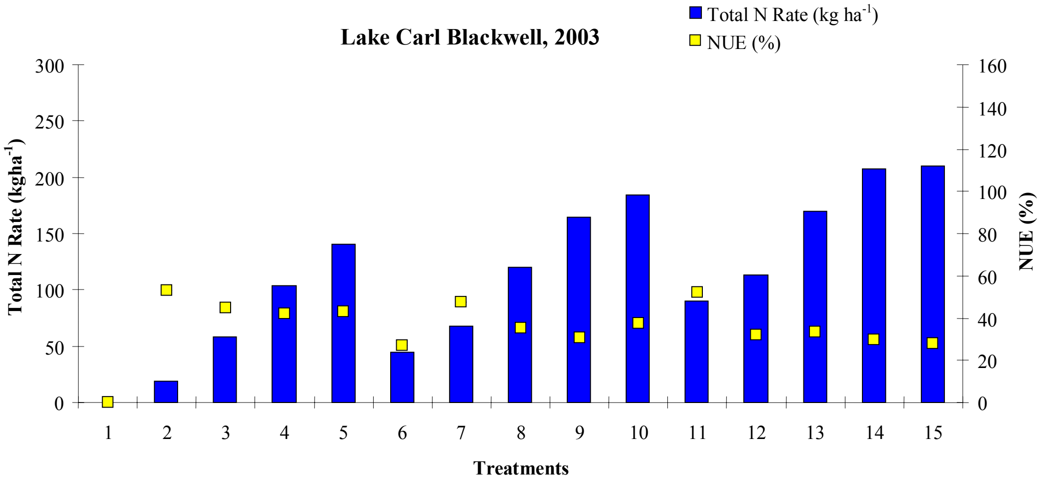


Figure 33. Treatments in respect to Total N Rate (kg ha^{-1}) and NUE (%), Lake Carl Blackwell, 2003

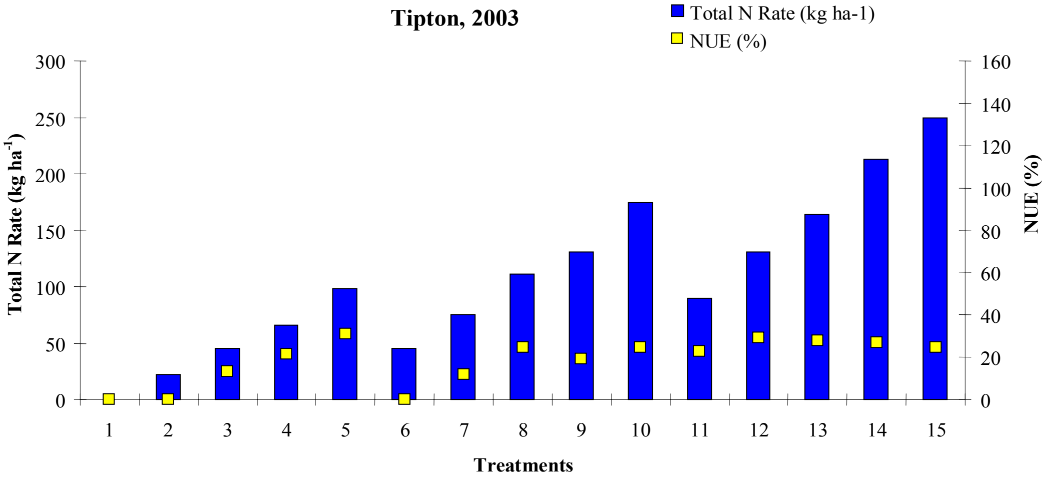


Figure 34. Treatments in respect to Total N Rate (kg ha^{-1}) and NUE (%), Tipton, 2003

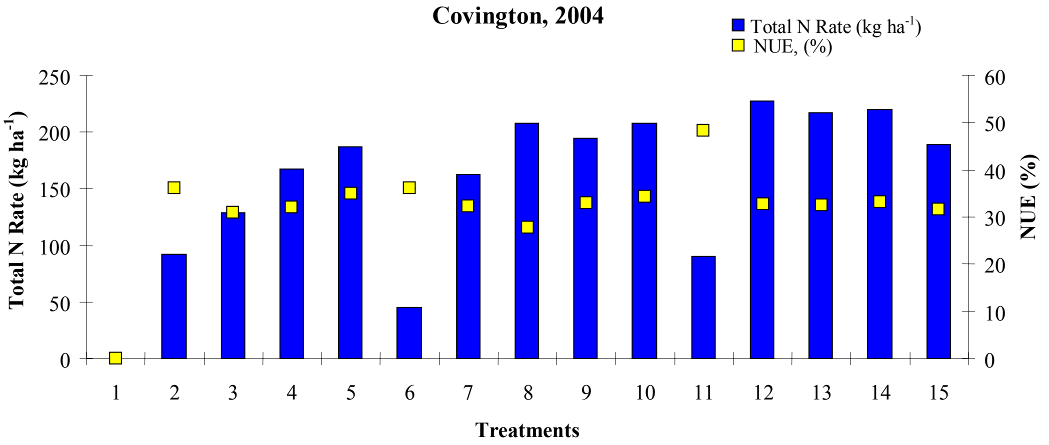


Figure 35. Treatments in respect to Total N Rate (kg ha^{-1}) and NUE (%), Covington, 2004

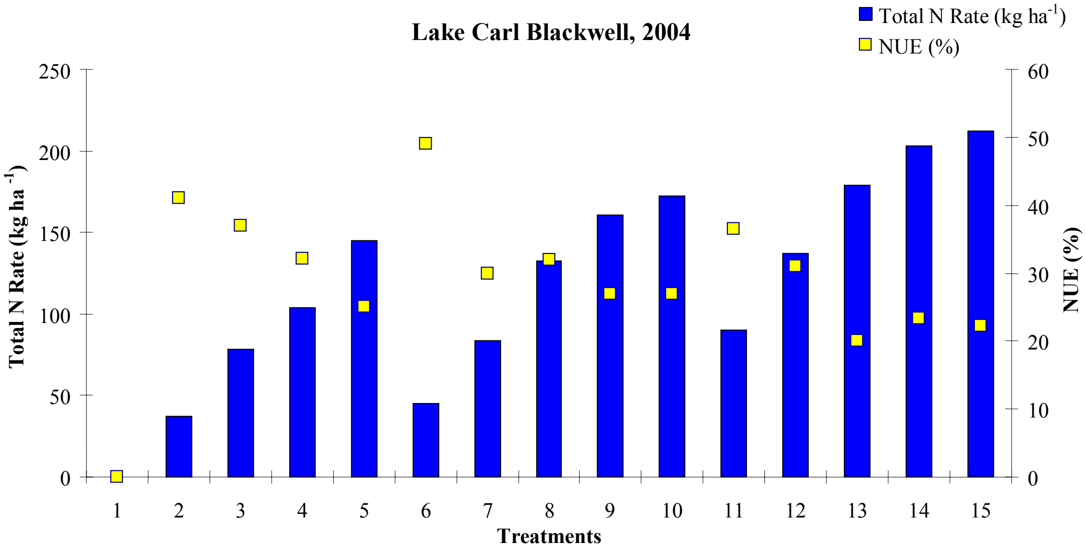


Figure 36. Treatments in respect to Total N Rate (kg ha^{-1}) and NUE (%), Lake Carl Blackwell, 2004

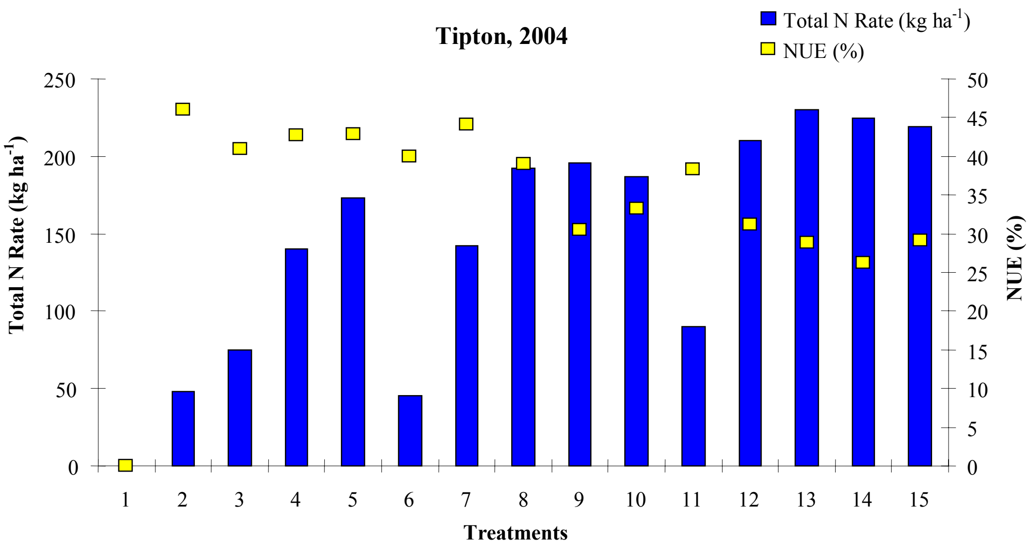


Figure 37. Treatments in respect to Total N Rate (kg ha^{-1}) and NUE (%), Tipton, 2004

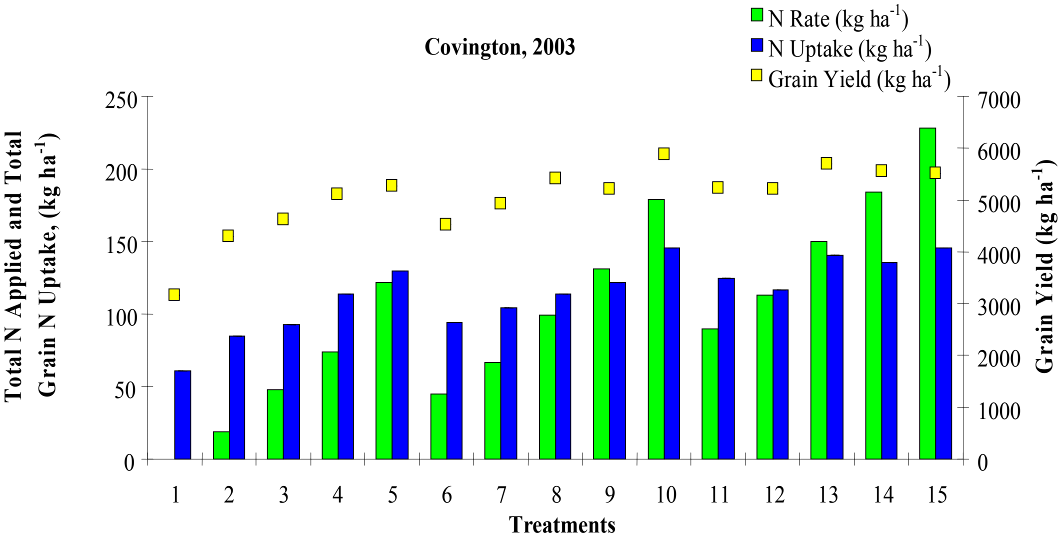


Figure 38. Treatments in respect to Total N Applied, Total Grain N-uptake, and Grain Yield, Covington, 2003

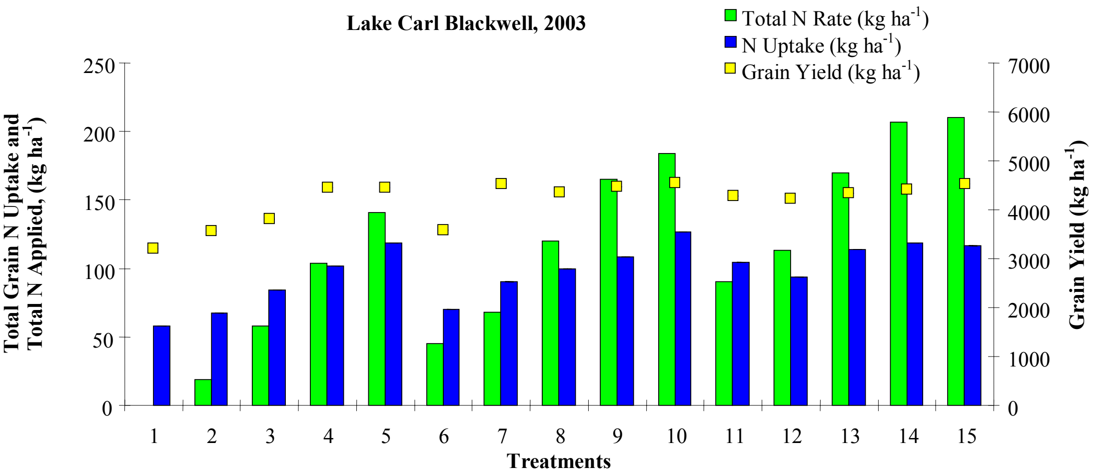


Figure 39. Treatments in respect to Total N Applied, Total Grain N-uptake, and Grain Yield, Lake Carl Blackwell, 2003

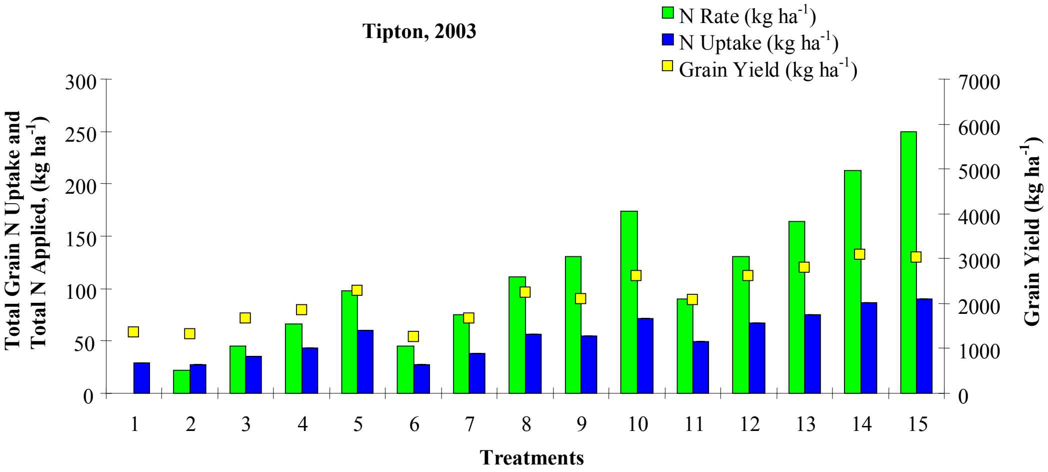


Figure 40. Treatments in respect to Total N Applied, Total Grain N-uptake, and Grain Yield, Tipton, 2003

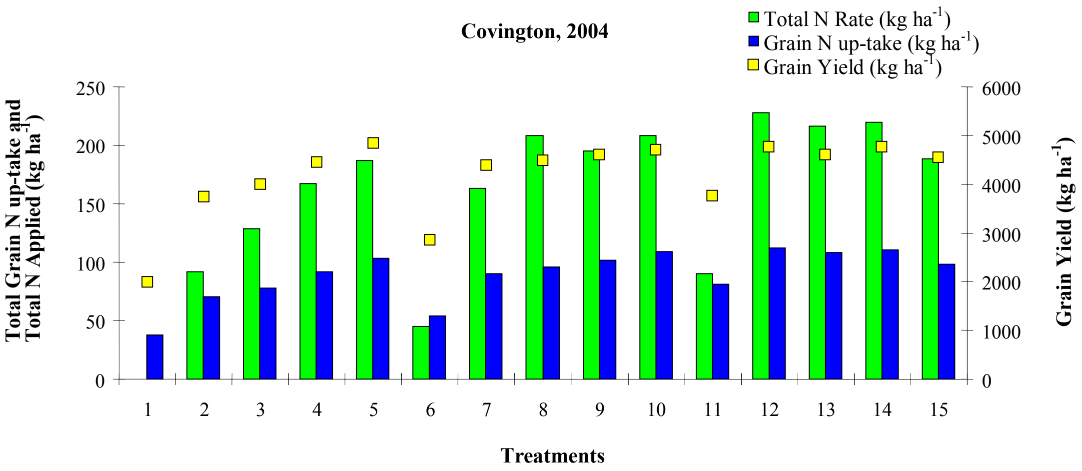


Figure 41. Treatments in respect to Total N Applied, Total Grain N-uptake, and Grain Yield, Covington, 2004

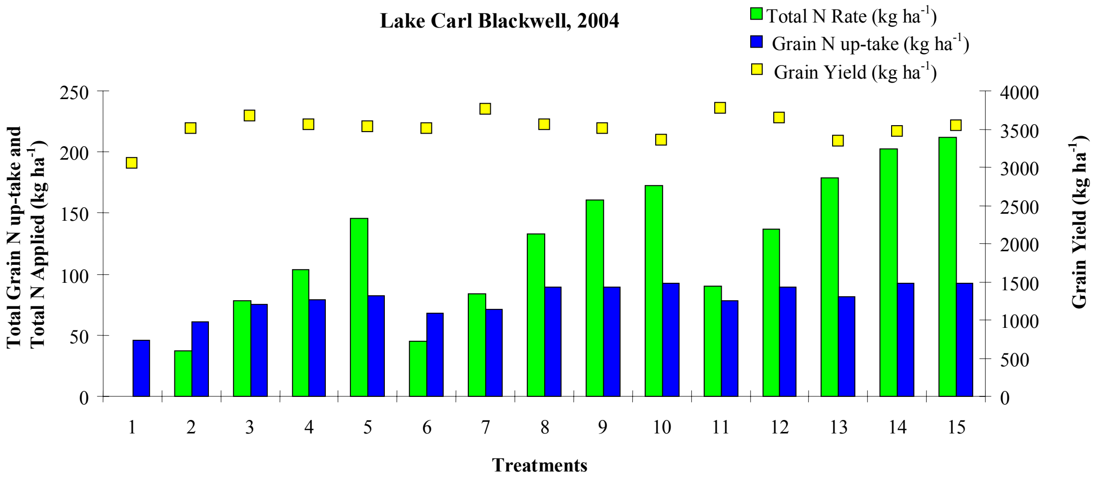


Figure 42. Treatments in respect to Total N Applied, Total Grain N-uptake, and Grain Yield, Lake Carl Blackwell, 2004

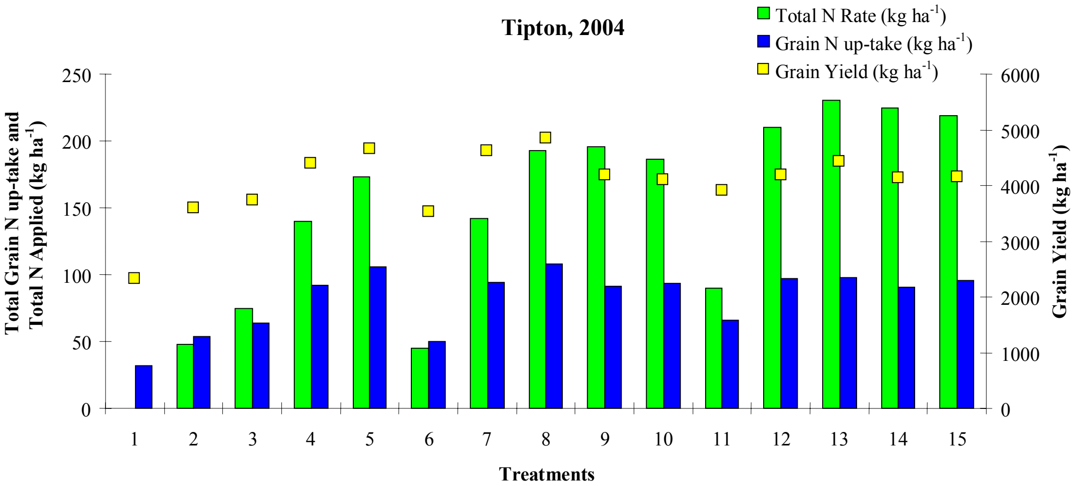


Figure 43. Treatments in respect to Total N Applied, Total Grain N-uptake, and Grain Yield, Tipton, 2004

Table 1. Total N applied, grain yield, and profit by location for Covington, Lake Carl Blackwell, and Tipton, 2003.

Treatment	Covington			Lake Carl Blackwell			Tipton		
	Total Applied N	Grain Yield	Profit	Total Applied N	Grain Yield	Profit	Total Applied N	Grain Yield	Profit
	-------kg ha^{-1}------		Dollars ha^{-1}	-------kg ha^{-1}-------		Dollars ha^{-1}	--------kg ha^{-1}------		Dollars ha^{-1}
1	0	3170	359	0	3207	366	0	1357	153
2	19	4295	477	19	3570	393	22	1311	139
3	48	4630	497	58	3802	399	45	1673	163
4	74	5122	534	104	4453	439	66	1859	173
5	122	5271	520	141	4453	417	98	2278	199
6	45	4527	476	45	3579	370	45	1264	110
7	67	4936	509	68	4527	462	75	1673	138
8	99	5419	550	120	4360	415	111	2240	176
9	121	5215	507	165	4472	402	131	2092	149
10	179	5875	546	184	4546	398	174	2612	183
11	90	5234	526	90	4276	419	90	2082	167
12	113	5225	512	113	4230	397	131	2612	203
13	150	5708	542	170	4341	377	164	2808	205
14	184	5569	506	207	4406	362	213	3086	206
15	228	5522	471	210	4537	375	250	3031	175

Table 2. Total N applied, grain yield, and profit by location for Covington, Lake Carl Blackwell, and Tipton, 2004.

Treatment	Covington			Lake Carl Blackwell			Tipton		
	Total Applied N	Grain Yield	Profit	Total Applied N	Grain Yield	Profit	Total Applied N	Grain Yield	Profit
	------kg ha^{-1}-------		Dollars ha^{-1}	-------kg ha^{-1}-------		Dollars ha^{-1}	-------kg ha^{-1}------		Dollars ha^{-1}
1	0	1985	261	0	3047	392	0	2329	305
2	86	3736	427	37	3507	429	48	3605	439
3	129	4000	438	78	3675	428	75	3739	439
4	167	4454	465	104	3552	394	140	4394	474
5	186	4831	504	145	3533	366	173	4657	487
6	45	2846	329	45	3502	416	45	3533	425
7	153	4391	452	84	3760	426	142	4625	500
8	208	4494	439	133	3556	367	193	4845	493
9	195	4598	457	161	3505	340	196	4189	404
10	208	4699	465	172	3355	315	187	4100	401
11	90	3751	415	90	3766	415	90	3909	433
12	228	4765	455	137	3649	367	210	4196	388
13	217	4601	436	179	3339	304	230	4275	410
14	220	4760	460	203	3471	306	224	4228	379
15	188	4551	455	212	3542	308	219	4154	382

VITA

Keri Brixey Morris

Candidate for the Degree of

Master of Science

Thesis: MID-SEASON RECOVERY TO NITROGEN STRESS IN WITER WHEAT

Major Field: Plant and Soil Sciences

Biographical:

Personal Data: Born in Jay, Oklahoma, on March 20, 1978.

Education: Graduated from Grove High School, Grove, Oklahoma in May 1996; received Associate of Art degree from Coffeyville Community College, Coffeyville, Kansas in May 1998; received Bachelors of Science degree in Plant and Soil Science from Oklahoma State University, Stillwater, Oklahoma in May, 2002. Completed the requirements for Master of Science degree with a major in Plant and Soil Sciences at Oklahoma State University in December 2004.

Experience: Employed by Oklahoma State University, Soil Water Forage Analytical Laboratory, 1999-2001, ; employed by Oklahoma State University, Department of Plant and Soil Sciences as field assistant for the soil fertility projects, 2001-2002; employed by Oklahoma State University, Department of Plant and Soil Sciences as a graduate research assistant, 2002 to present.

Name: Keri B. Morris Date of Degree: December, 2004

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: MID-SEASON RECOVERY TO NITROGEN STRESS IN WINTER WHEAT

Pages in Study: 56 Candidate for the Degree of Master of Science

Major Field: Soil Science

Scope and Method of Study: Winter wheat yields are directly affected by the amount of nitrogen (N) that is available to them for growth. Past research has indicated that spring application of N is more effective than fall application for winter wheat. This experiment was conducted to determine if potential yield reductions from early season N stress can be corrected using in-season N applications. Three experimental sites for two growing seasons (6 site - years) were used to evaluate 3 preplant N rates (0, 45, and 90 kg ha^{-1}), and a range of in-season topdress N rates. Topdress N amounts were determined using a GreenSeeker^{TM} hand held sensor and an algorithm developed at Oklahoma State University. Even when early season N stress was present (0-N preplant) N applied topdress at Feekes 5 resulted in maximum or near maximum yields at 4 of 6 sites when compared to other treatments receiving both preplant and topdress N.

Findings and Conclusions:

In 2002-2004, obtaining maximum wheat grain yields from topdress N applications in 0-N preplant plots was possible at four of the six locations. The CV's for the two sites that failed to reach maximum yield were higher than 18, and the CV's for the site where topdress N was applied to 0-N preplant plots that achieved maximum yield were below 18. Also, at three of the six sites, the RI estimated using in season NDVI readings was under estimated. Even when early season N stress was present (0-N preplant), N applied topdress at Feekes 5 resulted in maximum or near maximum yields at 4 of 6 sites when compared to other treatments receiving both preplant and topdress N. However, when compared to the conventional 90 kg ha^{-1} preplant N, mid-season N applied (0-N preplant) resulted in maximum yields at all 6 sites.

ADVISOR'S APPROVAL:______________Dr. William Raun______________