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Economics of Pre-Plant, Topdress, and Variable Rate Nitrogen Application in Winter Wheat

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Abstract

Past research about the efficiency of nitrogen application in winter wheat (*Triticum aestivum* L.) based on source and timing has produced inconsistent results. The majority of the literature used data from few locations over short time periods. This study used a unique data set of yields and nitrogen quantities from 2002-2009 at ten different locations in Oklahoma, USA. The objective of this research was to determine wheat yield response for granular pre-plant, uniform foliar topdress, and variable rate foliar topdress. Topdress liquid nitrogen had a 19% higher NUE than pre-plant urea, and was the most profitable source of nitrogen.

Key words: linear stochastic plateau - nitrogen use efficiency – profitability – wheat

Abbreviations: N, nitrogen; NUE, nitrogen use efficiency; ANOVA, analysis of variance; LCB, lake Carl Blackwell; ORM, optical reflectance measurements; VRT, variable rate treatment; URT, uniform rate treatment; UAN, urea ammonium nitrate; NRS, nitrogen rich strip.

Introduction

Nitrogen (N) is a costly and vital component in winter wheat (*Triticum aestivum* L.) production. The timing of applications and the source of N can affect the amount of N recovered or the nitrogen use efficiency (NUE) in a given year. In the Great Plains, wheat producers can apply N before planting or in mid-season as topdress. In addition, N can be applied as a granular or as a foliar/liquid, which is the form most precision systems use. Knowing the relative NUE of pre-plant and topdress is important information for producers to determine early season and/or mid-season N rates. Also, this information is valuable for calibrating precision N algorithms to be more accurate predictors of N needed to reach the potential yield plateau.

The majority of the nitrogen-response literature has focused on efficiency gains from split application of pre-plant and topdress, which makes it hard to determine exact efficiency gains or losses. The studies comparing NUE from pre-plant and topdress have reached inconsistent conclusions and used various sources of N. Blankenau et al. (2002) determined granular topdress to have a higher efficiency than granular pre-plant, and Wuest and Cassman (1992) found liquid application of topdress increases NUE relative to liquid pre-plant. Pre-plant N can be lost to denitrification and leaching from heavy rains, which explains why topdress can have a higher NUE than pre-plant (Aulakh et al. 1982, Harper et al. 1987, Raun and Johnson 1999). However, Brown and Petrie (2006) concluded winter wheat to have similar efficiency to urea pre-plant and urea topdress treatments, and Lopez-Bellido et al. (2006) found urea pre-plant to have equal NUE to topdress ammonium nitrate.[1]

Several studies have focused on efficiency gains from granular topdress, but few have examined the efficiency gains from liquid/foliar topdress. Woolfolk et al. (2002) and Bly and

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[1] The data in these studies came from areas with Mediterranean climate where summers are dry and most of the rainfall occurs in the winter months. Under these conditions, it is more likely for topdress N uptake to be limited.

Woodward (2003) discussed the advantages of foliar topdress application, but no comparisons were made to pre-plant or granular N. Also, Luther and Mahler (1988) found that foliar topdress (urea and ammonium nitrate) can increase NUE by 6% compared to granular topdress (ammonium nitrate), but does not relate this to pre-plant efficiency.

It is uncommon for the research that compares NUE across N sources (i.e., granular vs. liquid) and N application timing (i.e., pre-plant vs. topdress) to include more than three years of data from several locations. Weather and other stochastic events can impact N response in wheat production, and therefore estimating N response over a few years can be misleading. Bullock and Bullock (2000) and Bullock et al. (2009) argued that data from more than five years and five locations are needed to determine the effects of inputs and stochastic factors on yield.

Analysis of variance is a common method used by researchers to determine efficiency gains across treatments. An advantage of this method is that it does not impose a specific functional form, but a disadvantage is that it can lead to low power to reject the null hypothesis. Several production functions have been used by researchers to estimate yield response to inputs. Tembo et al. (2008) extended Maddala and Nelson's (1974) switching regression approach and developed a linear stochastic plateau function that incorporates random effects for site year and for the plateau. The function was derived to match Raun et al. (2002), and was successfully implemented by Biermacher et al. (2009b) and Roberts (2009) to analyze yield response to N applications in wheat production. The Tembo et al. (2008) approach is adapted here so that the slope for each N source can be different.

The objective of this study was to determine if the slopes for granular pre-plant, uniform foliar topdress, and variable rate foliar topdress were statistically different using the stochastic plateau function. The data used included yields over eight years and ten locations, which is unique to the literature. The estimated models were also used to find the expected profits under certainty and under uncertainty. The value of perfectly predicting the N needed to reach the plateau was found by subtracting the expected profits under uncertainty from the profits under certainty.

Material and Methods

Data

Long-term field experiments were conducted across Oklahoma, USA, regarding the response of winter wheat yield to nitrogen application. The data included yields and N quantities spanning from 2002 to 2009. The experimental plots were 6.0 m long by 4.0 m wide and were located near Altus, Perkins, Tipton, Hennessey, Covington, Lake Carl Blackwell (LCB), Lahoma, Haskell, Chickasha, and Perry Oklahoma, USA. Rainfall and soil characteristics for each location were summarized in Tables 1 and 2.

Ten N treatments were replicated three times at each location. The treatments were continuous, that is, the same N treatments were applied to the same plot every year. Continuous wheat is a common practice in Oklahoma and has been researched by the Oklahoma Agricultural Experiment Station for years (Girma et al. 2007; Davis et al. 2003). Six treatments were conventional uniform treatments that applied pre-determined amounts of N. Two treatments were true variable rate technology (VRT) that used optical reflectance measurements (ORM) to determine precise N amounts across the plots, and the remaining two treatments were uniform rate treatments (URT) that applied the average sensing rate uniformly. The VRT and URT treatments required a non-yield-limiting amount of N in late summer to a narrow strip, which was called the N rich strip (NRS). Wheat was planted in the fall, and in winter, sensor readings were taken from the wheat in the NRS and the wheat in the field to estimate the amount of N needed for the wheat to reach its plateau (Lukina et al. 2001; Raun et al., 2002, 2005; Solie et al. 2002). Finally, a liquid fertilizer applicator equipped with optical reflectance sensors as well as a GPS system was used to apply precise levels of N. The VRT amounts were based on the algorithm of Raun et al. (2005) or an earlier version of the algorithm (Raun et al. 2002, Solie et al. 2002). The N treatments were as listed in Table 3, with the first number representing the amount of kg ha^{-1} of pre-plant urea 46-0-0 and the last number representing the kg ha^{-1} of topdress urea ammonium nitrate 28-0-0 (UAN): 0/0, 0/45, 0/90, 45/45, 45/0, 90/0, 0/VRT, 45/VRT, 0/URT, and 45/URT. Average yields for the treatments across the locations are shown in Table 4. Urea was broadcast uniformly before planting in late September or early October, and UAN solution was applied during Feekes stage 4 through 6. GreenSeeker ™ Hand-held NTech Industries Inc sensors were used to determine N amounts for the VRT and URT treatments at each location.

Analysis Overview

First, an analysis of variance (ANOVA) was performed for the ten treatments to determine if mean yields were significantly different. Restrictions were then imposed such as a common intercept and yield plateau, and a linear stochastic plateau function was estimated to determine which N source was the most efficient. The slopes for pre-plant, topdress, and VRT indicated the relative efficiency of each source. Using the Raun et al. (2002) formula for NUE, the parameters estimated from the linear plateau function were translated into a NUE measurement. Also, equations from Tembo et al. (2008) were used to estimate the expected profit maximizing quantities of N. Expected profits were found under perfect knowledge of the plateau's location and for the profit maximizing quantities.

Analysis of Variance

ANOVA was performed using the MIXED procedure in SAS (SAS Institute Inc. 2004). Yield is the dependent variable and the independent variables were the ten N treatments. Random effects for site-year are included. The equation was expressed as

$$Y_{tli} = \alpha + \sum_{n=1}^{10} \beta_n X_{ni} + u_{tl} + \varepsilon_{tli} \tag{1}$$

where Y_{tli} is the yield in time period t, at location l, and on plot i; α is the yield intercept; x_{tli} is a binary variable for N treatment; β_n is yield response to the N treatment; $u_{tl} \sim N(0, \sigma_u^2)$ is the site-year random effect; and $\varepsilon_{tli} \sim N(0, \sigma_\varepsilon^2)$ is the random error term.

Stochastic Plateau

The linear stochastic plateau function assumed yield responds linearly to additional N until yield reached its plateau.[2] At the plateau, N was no longer a limiting factor of yield; thus, additional N does not increase yield. Random effects were included for the plateau and the intercept so that both vary randomly by year. The primary source of variability was expected to be rainfall, but

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[2] The experimental design does not give us sufficient data points to precisely estimate different effects for split applications since there are only three pre-plant levels of N. In theory, split applications can be modeled by pre-plant N having a nonlinear response. An attempt was made to estimate a quadratic term for pre-plant applications to capture the effect of split applications, but the quadratic term was not significant.

other random factors such as hail, freezes, disease, and insects can also affect yield potential. This response function was expressed as

$$y_{tli} = \min(\alpha + \sum_{n=1}^{3} \beta_n x_{tli}, \mu_m + v_{tl}) + u_{tl} + \varepsilon_{tli} \quad (2)$$

where y_{tli} is the wheat yield in the *t*th time period, at the *l*th location, and on the *i*th plot; α is the intercept; β_n, $n = 1, 2, 3$ represents yield response to pre-plant, topdress, and VRT; x_{tli} is the quantity of N applied; μ_m is the average plateau yield; $u_{tl} \sim N(0, \sigma_u^2)$ is the site-year random effect; $\varepsilon_{tli} \sim N(0, \sigma_\varepsilon^2)$ is the random error term; and $v_{tl} \sim N(0, \sigma_v^2)$ is the plateau random effect. Normality and independence was assumed across the three stochastic components. Equation (2) was estimated using the NLMIXED procedure in SAS 9.1 (SAS Institute Inc. 2004). The likelihood ratio test ($X^2_{(1,0.05)} = 3.84$) was used to determine if the N responses differ by pre-plant, topdress, and VRT. The key hypotheses tested were $\beta_1 = \beta_2$, $\beta_1 = \beta_3$, and $\beta_2 = \beta_3$.

Nitrogen Use Efficiency

NUE is a common measurement used by researchers to explain how agronomic factors can affect the amount of N recovered in a given year. A problem with NUE is that literature has used varied definitions of NUE, making it difficult to compare efficiency gains. Moll et al. (1982) defined NUE as grain yield divided by nitrogen supply, and Huggins and Pan (1993) discussed several extensions and modifications to the Moll et al. (1982) definition. Raun et al. (2002) defined NUE as the yield gains from applying N divided by that amount of N applied.

To calculate the optimal quantity of N needed to reach the plateau, Raun et al. (2002) assumed a value of NUE. The slope and plateau estimates from the linear stochastic plateau function can be used to determine the amount of N needed to reach the plateau under certainty and uncertainty. Using the stochastic plateau parameters, the NUE of pre-plant, topdress, and variable rate were derived by re-arranging Raun et al.'s (2002) optimal N equation. The slope parameters were transformed into NUE values for two purposes: (1) the NUE values were more understandable and usable than the slope estimates, and (2) realistic NUE values validate the model. Lukina et al. (2001) reported the realistic range of NUE in winter wheat to be 0.33 to 0.80. In this study, NUE under certainty was expressed as

$$\gamma = \tau(YP_N - YP_o) / N^A \tag{3}$$

where γ is the NUE; τ is 0.0239 the average percent of N in wheat; N^A is the amount of N reach the plateau; YP_N is the plateau yield; and YP_0 is the expected yield if no additional N is applied. ORM were taken from a nitrogen rich strip (NRS) and the farmer's field to find YP_N and YP_O. Once these measurements were taken, the algorithm calculated a deterministic amount of N required to reach the plateau or N^A. NUE was calculated by using parameter estimates from equation (2) and substituting them into equation (3). If the yield plateau is known as assumed by Raun et al. (2002), the resulting equation was

$$\gamma = \tau(\mu_m - \alpha) / N_n^* = \tau\beta_n \tag{4}$$

where the intercept α is the average yield if no additional N is applied or YP_o; and the expected yield plateau μ_m is the potential yield from applying additional N or YP_N. The optimal amount of

N is N_n^* for source *n*. If the yield plateau is not known, NUE will be lower due to applying more nitrogen than is needed in some years. Under plateau uncertainty, NUE was expressed as

$$(5) \qquad \gamma = \tau(E(y_n) - \alpha) / N_n^*$$

where $E(y_n)$ is the expected yield from applying N_n^*. $E(y_n) \leq \mu_m$, while N_n^* is known to be greater in the uncertainty case than in the certainty case given current prices.

Expected Profit Maximizing Quantity

The expected profit maximizing amount of N was estimated as in Tembo et al. (2008). Their formula considers the variance of the plateau in determining optimal N quantities, which differs from the deterministic approach used by Raun et al. (2002). The formula was derived in Tembo et al. (2008) equation [14] (2008, pg. 427) as

$$(6) \qquad N_n^* = \frac{1}{\beta_n}(\mu_m + Z_\alpha \sigma_v - \alpha)$$

where β_n is the parameter estimate for the *n*th source of N; μ_m is the plateau; σ_v is the plateau variance; α is the intercept; and Z_α is the standard normal probability of $r/(p\beta_n)$ (area in the upper tail), where the cost of fertilizer is *r* and the price of wheat is *p*.

The calculation of the expected yield with a stochastic plateau production function was presented by Tembo et al. (2008) in equation [6] (pg. 426) as

(7) $$E(y_n) = (1 - \Phi)a + \Phi(\mu_m - \frac{\sigma_v \phi}{\Phi})$$

where $a = \alpha + \beta_n N_n^*$,$\Phi = \Phi[a - \mu_m/\sigma_v]$ is the cumulative normal distribution function, and $\phi = \phi[a - \mu_m/\sigma_v]$ is the standard normal density function.

Net Returns

Expected profits were estimated for each N source using a partial budget, which is a common method for analyzing profitability of discrete alternatives. This study modified the partial budgets Biermacher et al. (2009a) developed for the ORM system. Profits were found for both the certainty and uncertainty cases. Expected profits were calculated as

(8) $$E(NR_n) = pE(Y_n) - r_n E(N_n^*) - E(AC_n) - ORM_n$$

where NR_n is the net return of the *n*th system; p is wheat price; Y_n is yield; r_n is the cost of N; AC_n is the application cost; and ORM_n represents the cost of optical reflectance sensing technology, including the NRS.

The expected profits for perfect information assume that the producer knows the exact location of the plateau in a given year. The goal of precision systems was to accurately predict the yield plateau. The value of perfect information was estimated by subtracting the profit for VRT under uncertainty from the profit under perfect knowledge.

The United States Department of Agricultural data were used to establish the price of wheat as \$0.18 kg^{-1}, the cost of urea \$0.90 kg^{-1}, and the cost of UAN as \$0.99 kg^{-1} (USDA 2009a; USDA 2009b). Application rates were from Oklahoma State Extension Service Fact

Sheets with an application cost for urea of \$9.18 ha^{-1} and UAN application cost of \$9.60 ha^{-1} (Doye, Sahs, and Kletke 2006; Doye and Sahs 2008). Boyer et al. (2009) estimated the cost of equipping a liquid fertilizer sprayer with six GreenSeeker ™ NTech Industries Inc sensors to be \$1.55 ha^{-1}, and the cost of the NRS in a 64.75 ha field to be \$2.23 ha^{-1}.

Results

Yields significantly differ by system at the 0.05 level using ANOVA. A Tukey-Kramer test was used to assess the statistical significance of paired comparisons. The control treatment (0/0) produced a significantly lower yield than all of the other treatments (0/45, 0/90, 45/45, 45/0, 90/0, 0/VRT, 45/VRT, 0/URT, and 45/URT). The 0/90 and 45/45 treatments were different from the 0/45 and the 45/0 treatment. However, no differences were found across the 0/90, 90/0, and 0/VRT treatments. On average, the uniform topdress (0/90) and the split (45/45) produced the highest yields (Table 4).

Table 5 shows the estimated stochastic plateau function. The intercept, which represents yield if zero N was applied, was 1515.6 kg ha^{-1}, and the expected plateau was 2189.7 kg ha^{-1}. The slope parameters differ across the three N sources with the smallest response coming from pre-plant and the largest response coming from topdress. Figure 1 displays the function for each N source. A larger slope allows wheat to achieve its yield plateau with less N, which suggests a higher efficiency. Using the likelihood ratio test, the topdress response was not significantly different from the VRT response ($p > 0.05$). The lack of statistical significance for VRT may be due to a lack of spatial variability on the small experimental plots. Topdress UAN was significantly different from pre-plant ($p < 0.05$). The topdress application of foliar UAN increases NUE by 19% over broadcast-applied pre-plant AN. Using ANOVA, no significant differences were found across topdress, pre-plant, and VRT, while topdress and pre-plant were different with the stochastic plateau function. The fewer parameters estimated with the linear stochastic plateau produces a more powerful test[3] than ANOVA.

The amount of N needed to reach the expected plateau was 37, 31, and 33 kg ha^{-1} of pre-plant, topdress, and VRT N; respectively (Table 6). The expected profit maximizing quantities when the plateau was unknown were 74, 69, and 71 kg ha^{-1} of pre-plant, topdress, and VRT. The reason the expected profit maximizing quantities were larger than the deterministic quantities was because the plateau variance was large, and the price of nitrogen was low relative to the price of wheat that can be produced from applying nitrogen when it was needed. The results translate into a deterministic NUE of 0.43, 0.51, and 0.49 for pre-plant, topdress, and VRT. These values were within the realistic range reported by Lukina et al. (2001) and were close to the value currently used in the Oklahoma State University precision algorithm.

Expected net returns assuming perfect information were \$351.52, \$353.54, and \$348.01 ha^{-1} for pre-plant, topdress, and VRT (Table 7), making topdress the most profitable source of N. For expected profit maximizing quantities, net returns were \$284.61, \$288.98, and \$281.59 ha^{-1}. The difference between the profit for VRT under perfect information and VRT under uncertainty was \$66.42 ha^{-1}. This number can be interpreted as the potential increase in net returns from predicting the exact location of the plateau. The potential gain from a perfect information system was much higher here than in previous research such as Biermacher et al. (2006). The reason for the difference was the data used in this research included more years and locations, which produced a higher plateau variance. This high plateau variance was at least partly due to adding 2008. In 2008, heavy rains in the fall created large potential yields and leached much of the

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[3] The power of the test is found by subtracting the type II error from 1; thus, the power of the test increase when type II error decreases. The type II error is not rejecting the null hypothesis when the alternative hypothesis is true (Wackerly, Mendenhall, and Scheaffer 2008).

nitrogen in the soil. For example, the most extreme case was Lahoma in 2008 where 0/0 had yields of 1,560 kg ha^{-1} and 0/90 had yields of 4,810 kg ha^{-1}. In addition, in 2007 and 2009, a freeze severely damaged Oklahoma wheat, which resulted in small yields. These extremes in possible yields lead to a high value of perfect information. While a sensing system might predict the high yields in 2008, it cannot predict the freeze damage and so the returns to perfect information are an upper bound that is not achievable.

Conclusions

The primary intent of this research was to determine the nitrogen use efficiency of topdress UAN relative to pre-plant urea. A unique large data set was used in this analysis that includes eight years of yields from 10 locations in Oklahoma, USA. A linear stochastic plateau was estimated that considers site year and plateau random effects to find yield response to pre-plant, topdress, and VRT. The stochastic plateau function proved to be a more powerful test than ANOVA.

A limitation of the data is that the plots used in the experiments were smaller than actual fields, and were likely to have less spatial variability than is found in actual farmer's fields. Less spatial variability may cause the uniform applications to have a relatively higher efficiency than what would be found in farmers' fields.

Topdress was believed to be more efficient than pre-plant since pre-plant N can be lost to denitrification and leaching from heavy rains. Foliar application was also believed to be more efficiently absorbed than granular application. Foliar topdress increased efficiency relative to uniform granular pre-plant by 19%. Even though urea has a per-unit cost advantage over UAN, the foliar topdress was the most profitable source of N. The potential value of perfect information was \$66.42 ha^{-1}, which was higher than what past research has estimated. The analysis of variance, however, shows that the past ORM systems were not able to capture this value of information.

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Table 1. Annual rainfall (in mm) across the locations and years in the data

Year	Perry[a]	Altus	Perkins	Lahoma	Haskell	Chickasha	LCB	Hennessey[a]	Tipton	Covington[a]
2002				739	967	736	905	928		928
2003	592	680		500				614	419	614
2004		660		845				975	773	975
2005		584	939	635			672	777	661	777
2006			622	458			660			
2007		541	1301	946			1440			
2008		537	1009	974			960			
2009			947	623			957			

Source: Oklahoma Mesonet (2009); Oklahoma Climatology Survey (2007).

[a] Annual rainfall data was not specifically available for Perry, Hennessey, and Covington. Rainfall reported for Perry comes from the Red Rock station, and the Marshall station rainfall totals are used for Hennessey and Covington.

Table 2. Soil characteristics at 25 cm across the locations

Locations	Texture	% Gravel	% Sand	% Silt	% Clay
Perry	Loam	0	36	42	22
Altus	Clay loam	1	24	40	36
Perkins	Loam	0	50	36	14
Lahoma	Clay loam	0	21	50	29
Haskell	Silt loam	0	21	68	11
Chickasha	Silt loam	0	19	42	40
LCB	Clay loam	0	25	48	27
Hennessey	Clay loam	0	21	50	29
Tipton	Loam	0	51	36	13
Covington	Sility clay loam	0	19	41	40

Source: Oklahoma Mesonet (2009); Biermacher et al. (2009a).

Table 3. Nitrogen treatments (in kg ha^{-1}) across all years and locations

Treatment	Amount of pre-plant applied	Amount of topdress applied
0/0	Zero	Zero
0/45	Zero	45
0/90	Zero	90
45/45	45	45
45/0	45	Zero
90/0	90	Zero
0/URT[a]	Zero	Uniform average sensing rate
45/URT[a]	45	Uniform average sensing rate
0/VRT[b]	Zero	Variable sensing rate
45/VRT[b]	45	Variable sensing rate

[a] Average sensing rate is found about averaging the amount of N estimated by the ORM system for each replication at the location.

[b] Variable rates of N determined by the ORM system.

Table 4. Average yield and N applied in kg ha^{-1} across all locations and years

Treatment	Altus	N	Lahoma	N	LCB	N	Perkins	N	Hennessy	N	Covington	N	Tipton	N	Chickasha	N	Haskell	N	Perry	N	Average[a]	N
0/0	2,414		1,622		2,164		993		3,392		2,076		1,768		3008		1267		3334		2,204	
0/45	2,778		2,526		2,412		1,196		3,558		2,769		2,341		3081		1371		4134		2,617	
0/90	2,809		3,289		2,585		1,410		3,756		3,076		2,664		1938		1158		4796		2,748	
45/45	2,774		3,377		2,406		1,235		3,836		3,219		2,660		2141		1311		4449		2,741	
45/0	2,609		2,400		2,379		1,188		3,860		2,849		2,208		2839		1238		4165		2,574	
90/0	2,728		3,051		2,433		1,440		3,618		2,979		2,347		2191		1169		4430		2,639	
0/URT	2,703	44	2,660	63	2,282	26	1,080	33	3,737	45	2,715	39	2,320	31	2625	12	1287	3	3781	17	2,519	31
45/URT	2,731	30	3,187	35	2,319	15	1,150	13	3,701	21	3,147	36	2,669	29	2375	10	1382	4	4606	22	2,727	21
0/VRT	2,822	49	2,275	76	1,764	27	1,243	35	3,630	86	1,093	27	1,689	42							2,074	49
45/VRT	2,780	25	2,425	39	1,700	17	1,312	15	3,621	29	1,240	10	2,306	33							2,198	24

[a] This value represents the average yield for each treatment across all ten locations and eight years.

[b] An analysis of variance was performed, and the 0/0 application was statistically different from the other treatments. Also, the 0/90 and 45/45 differed from the 0/45 and 45/0 treatments.

Table 5. Regression results for yield response across the three N sources

Statistic	Symbol	Parameter Estimate[a]
Intercept	α	1515.6 (30.54)
Pre-plant N[b]	β_1	18.13 (0.81)
Topdress N[b]	β_2	21.51 (0.87)
VRT N[b]	β_3	20.36 (0.14)
Expected yield plateau	μ_m	2189.7 (17.56)
Plateau random effects	σ_v	1112.16 (55.53)
Site-year random effects	σ_u	1054.56 (25.92)
Standard deviation of error term	σ_ϵ	213.96 (3.79)

[a] Standard errors are displayed in parenthesis.

[b] The likelihood ratio (LR) test is used to determine if there is a difference across the N sources. If the LR statistic is greater than the critical value of 3.84 then the conclusion is there is a difference. Topdress is different from pre-plant ($p < 0.05$) and topdress is not different from VRT ($p > 0.05$).

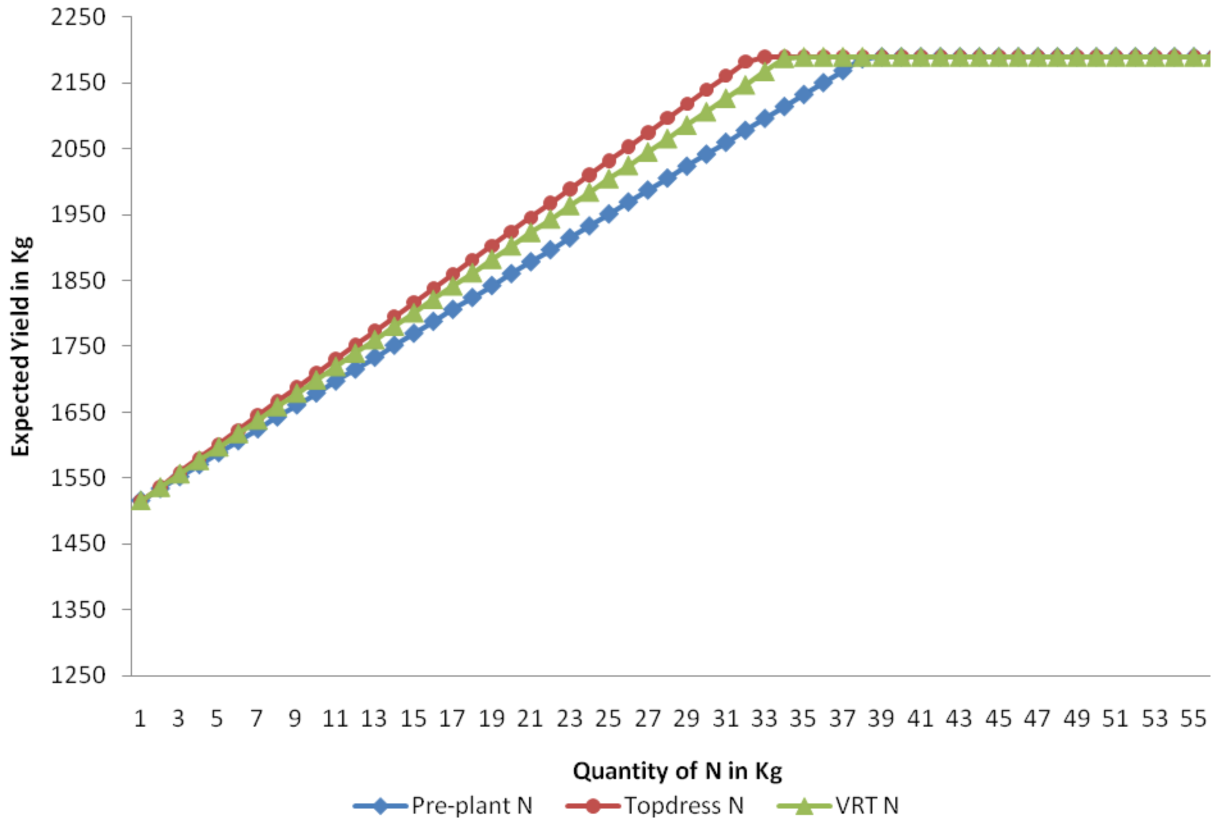

Figure 1. Yield response to pre-plant, topdress, and VRT N

Table 6. Amounts of N estimated under perfect information and uncertainty and average NUE for each N source

Quantity of N	Pre-plant	Topdress	VRT
Perfect information	37.16	31.32	33.09
Uncertainty	73.71	69.12	70.72
NUE[a]	0.43	0.51	0.49

[a] The NUE values reported are deterministic or under certainty. Under imperfect information, the NUE values are 0.22, 0.23, and 0.23 for pre-plant, topdress, and VRT.

Table 7. Expected net returns ($ in ha^{-1}) for perfect information and expected profit maximization

	Perfect information		
Net returns	Pre-plant	Topdress	VRT
Price of wheat	$0.18	$0.18	$0.18
Expected yield	2189.7	2189.7	2189.7
Total revenue	$394.15	$394.15	$394.15
Price of N	$0.90	$0.99	$0.99
N quantity	37.16	31.32	33.09
Total N costs	$33.44	$31.01	$32.76
Application cost	$9.18	$9.60	$9.60
Technology cost	0	0	$1.55
NRS cost	0	0	$2.23
Expected net returns	$351.52	$353.54	$348.01

	Expected profit maximization with uncertain plateau		
Net returns	Pre-plant	Topdress	VRT
Price of wheat	$0.18	$0.18	$0.18
Expected yield	2000.70	2038.92	2027.67
Total revenue	$360.13	$367.01	$364.98
Price of N	$0.90	$0.99	$0.99
N quantity	73.71	69.12	70.72
Total N costs	$66.34	$68.43	$70.01
Application cost	$9.18	$9.60	$9.60
Technology cost	0	0	$1.55
NRS cost	0	0	$2.23
Expected net returns	$284.61	$288.98	$281.59