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Optimal Nitrogen Fertilization Rates in Winter Wheat Production as Affected by Risk, Disease, and Nitrogen Source

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Interactions among the nitrogen (N) fertilization rate, N source, and disease severity can affect mean yield and yield variance in conservation tillage wheat production. A Just-Pope model was used to evaluate the effects of N rate, N source, and disease on the spring N-fertilization decision. Ammonium nitrate (AN) was the utility-maximizing N source, regardless of risk preferences. The net-return-maximizing AN rate was 92 lb N/acre, providing $0.52/acre higher net returns than the best alternative N source (urea). If a farmer could anticipate a higher-than-average Take-All Root Rot infection, the difference in optimal net returns between AN and urea would increase to $35.11/acre.

Key Words: Certainty equivalent, Glume-Blotch, nitrogen fertilizer, nitrogen source, risk, Take-All, winter wheat

JEL Classifications: D21, D81, Q12

Efficient spring nitrogen (N) fertilization practices increase the economic benefit of N in wheat production (Fiez, Pan, and Miller). Although N fertilization increases wheat yield, it can also affect production risk as measured by yield variability (Just and Pope 1979). In addition, interactions among N source (e.g., ammonium nitrate vs. urea), N rate, and disease severity can affect yield (Brennan 1992a,b; Colbach, Lucas, and Meynard; MacNish; Wiese) and may also affect production risk, leading some farmers to apply nonoptimal amounts of N fertilizer (Peters et al.). Farmers may be able to achieve greater utility by adjusting the N-fertilization rate and N source to account for the influence of N rate, N source, and disease on risk in wheat production.

Nitrogen fertilization was found to be risk increasing (Just and Pope 1979; Larson et al. 2001; Roumasset et al.) and risk reducing (Antle and Crissman; Lambert; Larson et al. 1998). The potential effect of N fertilizer on risk is influenced by the crop production system (e.g., conservation vs. conventional tillage) and other management factors in addition to N fertilization (Larson et al. 2001). Although these studies evaluated the effects of risk on N fertilization, they did not evaluate the risk effects of alternative N sources in the presence of disease.

Glume-Blotch is a late-season grain-head infection (Ditsch and Grove) that is found in all wheat-growing areas of the world (Bowden). It

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is most prevalent in high-rainfall, humid areas (Stromberg) such as the southern United States (Howard et al.). Fungicide applications are often incomplete in controlling Glume-Blotch (Bowden). Although N fertilization is essential for increasing the soft red winter wheat (wheat) yield, high spring N-fertilization rates can interact with Glume-Blotch to reduce yield potential (Boquet and Johnson). The lush vegetative growth that accompanies high N fertilization reduces air movement through the canopy, producing an environment that is more suited for Glume-Blotch development (Ditsch and Grove; Wiese). Without fungicide application in the presence of Glume-Blotch, higher N rates significantly reduced wheat yield (Cox et al.; Ditsch and Grove; Howard, Chambers, and Logan; Kelley; Roth and Marshell). Roth and Marshell showed that Glume-Blotch severity was lowest at an N rate of zero and increased for rates above 70 lb N/acre; however, Orth and Grybauskas found that higher levels of N significantly decreased susceptibility to Glume-Blotch infection. Although these studies found that the N rate affects Glume-Blotch severity and yield, they did not evaluate the effects of N rate and Glume-Blotch severity on risk and the N-fertilization decision. In addition, we found no other studies that evaluated the effects of Glume-Blotch severity and risk on optimal N fertilization.

The lack of resistant varieties and chemical control make the fungal root disease Take-All Root Rot (Take-All) the most important wheat root disease in the United States and in the world (Duffy and Weller; Monsanto). The severity of Take-All in wheat production was influenced by the N source, with more severe root damage in plots fertilized with nitrate (NO_3^-) than those fertilized with ammonium (NH_4^+) (Brennan, 1992a,b; Colbach, Lucas, and Meynard; MacNish; Wiese). Ammonium fertilizers may reduce Take-All severity because of a decreased rhizosphere pH that promotes more vigorous root growth, allowing roots to escape severe disease damage (Brennan, 1989). Brennan (1992a) found that 100 lb N/acre significantly reduced Take-All severity when ammonium forms of N were applied to wheat. However, where Take-All was at high levels, ammonium forms of N were ineffective in reducing Take-All severity (MacNish). Howard et al. found that ammoniacal N sources (ammonium nitrate and ammonium sulfate) resulted in higher wheat yields than urea-containing N sources (urea and urea-ammonium nitrate) when Take-All was present. Yield losses for the urea-containing N sources were probably caused by volatilization N losses and disease. These studies showed that the N source and rate can affect Take-All severity and yield; however, they did not evaluate the effects of N rate, N source, and Take-All severity on risk and the optimal wheat N-fertilization decision.

A comprehensive evaluation of the interactions among N rate, N source, Glume-Blotch and Take-All severity, and their effects on expected wheat yield and risk was not found (Walters). The objectives of the present study were to (1) evaluate the effects of N source, N rate, and disease severity on risk, optimal N rate, expected yield, and net returns in conservation tillage wheat production and (2) evaluate the risk-return tradeoffs among alternative N sources for farmers with different risk preferences.

Yield Data

Wheat yields for 1998–2000 were obtained from an N-fertilization experiment on conservation tillage wheat at the West Tennessee Experiment Station, Jackson, Tennessee (Howard et al.). Planting dates were 22 October 1997, 9 October 1998, and 15 October 1999. The experimental design was a randomized complete block with split plots. Treatments were replicated five times. Main plots were treated with 0, 30, 60, 90, 120, and 150 lb N/acre around 1 March at Feekes' growth stage (GS) 6 (Large) when the first node of the stem was visible. Subplots included three N sources: ammonium nitrate (AN), urea, and urea-ammonium nitrate (UAN). AN and urea were broadcast as dry fertilizers, whereas UAN was broadcast as a liquid. Individual plots were 40 feet long and 12 feet wide. Glume-Blotch affected the 1998 crop and Take-All affected the 2000 crop. Both diseases occurred naturally. In 1998, Propiconazole was applied at

Table 1. Descriptive Statistics for Variables Used in the Just-Pope Model

	Nitrogen Source[a]					
	AN		Urea		UAN	
Variable[b]	Mean[c]	SD	Mean[c]	SD	Mean[c]	SD
Y	59.34	19.41	57.43	21.99	55.56	21.64
N	75.00	51.52	74.49	51.59	75.00	51.52
Glume-Blotch Rating	2.06	3.15	1.86	2.84	1.63	2.49
G	−2.49	3.02	−2.50	2.98	−2.56	2.91
Take-All Rating	1.02	1.86	1.19	2.14	1.36	2.32
TA	−2.77	2.64	−2.75	2.71	−2.65	2.79
n	90		89		90	

[a] Nitrogen sources are ammonium nitrate (AN), urea, and urea-ammonium nitrate (UAN).

[b] Y is wheat yield (bu/acre); N is nitrogen applied (lb/acre); G is the natural logarithm of the Glume-Blotch rating from 0.01 to 10, with 0.01 being no disease present and 10 being the most severe disease rating; and TA is the natural logarithm of the Take-All rating from 0.01 to 10, with 0.01 being no disease present and 10 being the most severe rating.

[c] Three-year means and standard deviations (SD).

0.030624 gal/acre at GS 9 with a second application at GS 10 before heading. In 1999 and 2000, a single application of Quadris was applied at 0.0616704 gal/acre at GS 9. Propiconazole and Quadris are both foliar fungicides used to control Glume-Blotch severity (Bailey). No chemicals were applied to control Take-All because no effective chemical control exists to limit Take-All severity (Colbach, Lucas, and Meynard). Disease ratings were recorded each year at GS 10.1, when the sheath of the last leaf was completely grown out. Disease ratings were recorded on a scale of 0 to 10, with 10 being the most severe disease rating. Plots were harvested during mid-June.

Methods

Farmers can use measures of expected net return and net-return variance to make agricultural production decisions such as the one addressed in the present article (Barry). The Just-Pope (1978, 1979) model was chosen to evaluate the risk-return tradeoffs of the N-fertilization decision in wheat production. This method isolates the effects of changes in input use on expected yield and yield variance. Among others, this method has been used to evaluate the risk effects of (1) N as a non–point pollution problem with alternative policies and farmer response to those policies (Lambert); (2) genetic improvement on wheat yields during the green revolution (Traxler et al.); (3) winter cover crop, tillage, and N-fertilization systems in cotton production (Larson et al. 2001); (4) genetic resources and diversity variables in wheat production (Smale et al.); (5) variable-rate N application in corn production (Larson, English, and Roberts); (6) integrated pest management in cotton production (Hurd); and (7) input use in farm-raised salmon production (Asche and Tveteras). Results from the Just-Pope model can be used to determine the level of input that maximizes the certainty-equivalent net return (Lambert; Larson, English, and Roberts; Larson et al. 2001).

The Just-Pope model takes the form

$$(1) \qquad Y_t = f(X_t, \beta) + h^{1/2}(Z_t, \alpha)\varepsilon_t,$$

where Y is wheat yield, X and Z are matrices of explanatory variables, t is a subscript for year, β and α are parameter vectors, ε is a random error term with a mean of zero, f is the mean yield production function that relates X_t to mean yield, and $h^{1/2}$ is the yield standard deviation function that associates Z_t with yield standard deviation and with yield variance through h.

Data from the aforementioned experiment (Table 1) were used to evaluate the N-fertilization decision in wheat production as affected by three N sources, two diseases, six N-fertilization rates, and risk under the maintained assumption that the farmer attempts to control Glume-Blotch with the fungicides in the amounts applied in the experiment or ones of similar effectiveness. This maintained assumption was needed because the same amount of fungicide was applied each year to all plots, and a fungicide application variable would produce perfect collinearity in the econometric analysis of the Just-Pope model.

The mean yield production function for each N source was estimated as

$$(2) \quad Y_t = \beta_0 + \beta_1 N_t + \beta_2 N_t^2 + \beta_3 G_t + \beta_4 N_t \times G_t + \beta_5 TA_t + \beta_6 N_t \times TA_t + e_t,$$

where Y was wheat yield (bu/acre); N was the N rate (lb/acre); G was the natural logarithm of the Glume-Blotch rating from 0.01 to 10, with 0.01 being no disease present and 10 being the most severe disease rating; $N \times G$ was the interaction between N and G; TA was the natural logarithm of the Take-All rating from 0.01 to 10, with 0.01 being no disease present and 10 being the most severe disease rating; $N \times TA$ was the interaction between N and TA; β_i $(i = 0, 1, \ldots, 6)$ were parameters to be estimated; and e was a random error with a mean of zero.

The quadratic functional form for N was chosen because low amounts of N fertilization generally increase wheat yields, whereas excessive N fertilization can reduce wheat yields by increasing the potential for lodging and delayed maturity (Beuerlein and Lipps; McKenzie; Vitosh). Yield response to N fertilization was hypothesized to exhibit diminishing marginal productivity ($\beta_1 > 0$, $\beta_2 < 0$).

The Glume-Blotch and Take-All severity ratings in the experiment were visual ratings related to the condition of the wheat plant. Implicit in the logarithmic functional forms for these disease ratings was the assumption that increases in ratings at the lower end of the scale (e.g., from 1 to 2) reduce yields by larger amounts than increases in ratings at the upper end of the scale (e.g., from 9 to 10). The logarithmic functional form required that the zero disease rating be replaced by a number close to zero, in this case 0.01, because the natural logarithm of zero is undefined. Glume-Blotch severity (β_3 and β_4) and Take-All severity (β_5 and β_6) were hypothesized to negatively influence yield.

Error sums of squares from ordinary least-squares (OLS) regressions of the mean yield functions were used to develop F-tests for identifying significant differences in yield variances between N sources. Significant differences in error sums of squares can help rank the yield variances of the N sources.

Efficiency gains in parameter estimates are possible with weighted least-squares (WLS) when multiplicative heteroscedasticity is found. Multiplicative heteroscedasticity in the mean yield functions was tested using the Breusch-Pagan statistic (Breusch and Pagan) and the model F-statistic from the yield variance functions described below (Judge et al.). When evidence of heteroscedasticity was found for a particular N source, predicted values from the estimated yield variance function were used as weights in producing WLS estimates for the mean yield function for that N source.

An exponential yield variance function was estimated for each N source as (Hurd; Traxler et al.)

$$(3) \quad \ln \hat{e}_t^2 = \alpha_0 + \alpha_1 N_t + \alpha_2 N_t^2 + \alpha_3 G_t + \alpha_4 N_t \times G_t + \alpha_5 TA_t + \alpha_6 N_t \times TA_t + u_t,$$

where $\ln \hat{e}_t^2$ was the natural logarithm of the squared residuals from the estimation of Equation (2), α_i $(i = 0, 1, \ldots, 6)$ were parameters to be estimated, and other variables were as defined in Equation (2). Although u_t does not have a zero mean, this specification allowed asymptotically valid hypothesis testing of the marginal risk effects of the explanatory variables (Harvey; Hurd; Traxler et al.).

Previous literature did not lend itself to developing firm hypotheses about the signs of the N parameters in Equation (3) (α_1, α_2, α_4, and α_6). Several previous studies found that N fertilization increased risk (e.g., Roumassett et al.), whereas others found that it reduced risk (e.g., Antle and Crissman; Lambert). Therefore, the expected effect of N rate on wheat yield variance was uncertain.

Larson et al. (2001) hypothesized that increased weed and insect pressure would increase yield variance in cotton production. As with weed and insect pressure, Glume-Blotch and Take-All may increase wheat yield variance because of their random effects on yields, but they may also decrease yield variance if they tend to equalize yields by disproportionately reducing yields in highly productive areas of a field and in good weather years when lush vegetative growth is more conducive to disease development. Thus, the effects of Glume-Blotch and Take-All severity on yield variance were uncertain.

The partial derivatives of the exponential of Equation (3) with respect to the N rate, Glume-Blotch rating, and Take-All rating (Table 1) were evaluated at the means of the variables for each N source to estimate marginal effects on risk. Joint *F*-statistics were used to test the null hypothesis that the coefficients for N, N^2, $N \times G$, and $N \times TA$ were jointly equal to zero for each N source. Rejection of the null hypothesis for a particular N source would suggest that N rate significantly affected yield variance when N was applied using that N source. In addition, pairwise *F*-tests were performed to examine the null hypothesis that the coefficients for these variables were the same between N sources. Differences in these coefficients between N sources would suggest that the N rate affected yield variance differently between N sources. Similar *F*-tests were performed for the Glume-Blotch severity coefficients (G and $N \times G$) and the Take-All severity coefficients (TA and $N \times TA$).

The estimated mean yield response and yield variance functions for each N source were used to predict certainty-equivalent–optimizing N-fertilization rates, yields, and net returns above N costs. Expected net returns above N costs and net-return variances were calculated using an average wheat price of \$3.43/bu for 1991–2000 (Tennessee Department of Agriculture). Wheat prices were inflated to 2002 dollars by the Gross Domestic Product Implicit Price Deflator (U.S. Department of Commerce, Bureau of Economic Analysis) before averaging. Average retail prices paid by Tennessee farmers in 2002 for pure N were AN, \$0.26/lb; urea, \$0.21/lb; and UAN, \$0.23/lb (Duke, personal communication, Tennessee Farmers Cooperative). These prices included the cost of application equipment but not the cost of the tractor to pull the equipment. Tractor costs were assumed to be equal across N sources, because these dry and liquid N sources have about the same tractor-size and speed requirements for broadcast application. Other wheat-production costs were also assumed to be constant among N sources.

The certainty equivalent net return per acre (CE) was approximated as (Robison and Barry)

$$(4) \qquad CE = E(NR) - \lambda/2 \ \mathrm{Var}(NR),$$

where $E(NR)$ was expected net return, λ was the Pratt-Arrow absolute risk aversion coefficient, and $\mathrm{Var}(NR)$ was the variance of net returns. Freund showed that the linear mean-variance objective function is consistent with normally distributed profits and the negative exponential utility function (or exponential utility function), which exhibits constant absolute risk aversion. $E(NR)$ was calculated as

$$(5) \qquad E(NR) = (\hat{Y} \times \overline{WP}) - (\hat{N} \times \overline{NP}),$$

where $\hat{Y}$ was mean wheat yield predicted from the mean yield function estimated in Equation (2) (bu/acre), $\overline{WP}$ was the average wheat price from 1991–2000 in 2002 dollars (\$/bu), $\hat{N}$ was the N rate associated with $\hat{Y}$ (lb/acre), and $\overline{NP}$ was the 2002 price of pure N (\$/lb). $\mathrm{Var}(NR)$ was calculated as (Bohrnstedt and Goldberger)

$$(6) \qquad \mathrm{Var}(NR) = (\hat{Y}^2)\sigma^2_{WP} + \overline{WP}^2(\sigma^2_{\hat{Y}}) + \sigma^2_{WP}(\sigma^2_{\hat{Y}}),$$

where σ^2_{WP} was the wheat price variance from 1991 to 2000, in 2002 dollars (\$/bu); $\sigma^2_{\hat{Y}}$ was the variance of wheat yield obtained by taking the exponential of the yield variance function estimated in Equation (3) (bu/acre); and other variables were as defined in Equation (5).

Table 2. Estimated Mean Wheat Yield Response Functions for Alternative N Sources

	Nitrogen Source		
Variable[a]	AN[b]	Urea[c]	UAN[c]
Intercept	11.54*** (2.74)[d]	11.20*** (3.78)	11.89*** (3.25)
N	0.55*** (0.05)	0.29*** (0.08)	0.29*** (0.06)
N^2	−0.0026*** (0.0003)	−0.0010*** (0.0004)	−0.0011*** (0.0003)
G	−4.33*** (0.48)	−4.64*** (0.61)	−4.94*** (0.54)
$N \times G$	0.004 (0.005)	−0.001 (0.007)	0.005 (0.006)
TA	−6.02*** (0.64)	−5.94*** (0.66)	−5.49*** (0.55)
$N \times TA$	−0.005 (0.006)	−0.023*** (0.008)	−0.025*** (0.006)
Adjusted R^2	0.89	0.85	0.90
n[e]	90	89	90
Yield-Maximizing N Rate (lb/acre)[f]	106.5	177.9	156.1
Maximum Wheat Yield (bu/acre)[f]	68.5	70.8	65.9

[a] Wheat yield (bu/acre) is the dependent variable; N is nitrogen applied (lb/acre); G is the natural logarithm of the Glume-Blotch rating from 0.01 to 10, with 0.01 being no disease present and 10 being the most severe disease rating; $N \times G$ is the interaction between N and G; TA is the natural logarithm of the Take-All rating from 0.01 to 10, with 0.01 being no disease present and 10 being the most severe disease rating; and $N \times TA$ is the interaction between N and TA.

[b] Ordinary least-squares results.

[c] Weighted least-squares results.

[d] Numbers in parentheses are standard errors.

[e] Urea has one less observation because of missing data.

[f] Evaluated at 3-year mean of the variables.

*** Significantly different from zero at the 1% level.

The CE-maximizing N fertilization rate for each N source was found by solving

$$(7) \quad \text{Max } CE = E(NR) - \lambda/2 \, \text{Var}(NR), \qquad \text{s.t.} \quad 0 \leq N \leq 150 \text{ lb N/acre}.$$

Maximum CE was constrained within the range of N-fertilization rates in the experimental data. Equation (7) was solved for risk neutrality ($\lambda = 0$) and two levels of risk aversion ($\lambda = 0.01$ and $\lambda = 0.02$), consistent with the range of risk aversion evaluated by Lambert and Larson et al. (2001).

Results and Discussion

Mean Yields

The estimated mean wheat yield functions are presented in Table 2. The mean yield functions for urea and UAN were estimated with WLS after Breusch-Pagan statistics, and the F-statistic from the yield variance function for urea suggested the possibility of multiplicative heteroscedasticity (Table 3). The adjusted R^2 coefficients in Table 2 suggest that considerable amounts of variation in wheat yields were explained by the nitrogen and disease variables. The coefficients for N and N^2 had the hypothesized signs and were statistically significant for each N source. Glume-Blotch (G) and Take-All (TA) severity significantly reduced wheat yields for each N source, as did the N–Take-All interactions ($N \times TA$) for urea and UAN. The N–Take-All interaction for AN and the N–Glume-Blotch interactions ($N \times G$) for all N sources were not significantly different from zero. Multicollinearity diagnostics found that the N sources did not have condition indexes greater than 20, which was the lower threshold suggested by Belsley, Kuh, and Welsch, which indicates that the standard errors were not seriously degraded.

Maximum wheat yields of 68.5, 70.8, and 65.9 bu/acre were obtained at 106.5, 177.8, and 156.1 lb N/acre for AN, urea, and UAN

Table 3. Heteroscedasticity Tests for the Mean Wheat Yield Functions and Ordinary Least-Squares (OLS) Error Sums of Squares

	Nitrogen Source		
Statistic	AN	Urea	UAN
Breusch-Pagan	5.85	23.09***	17.25***
Yield Variance Equation *F*-statistic	0.64	2.85***	0.75
OLS Error Sums of Squares[a]	3,474	3,677	3,510

[a] Values were not significantly different from one another at the 10% level. *F*-tests comparing error sums of squares for urea and AN, urea and UAN, and UAN and AN were 1.07 (*df* 82/83), 1.06 (*df* 82/83), and 1.01 (*df* 83/83), respectively.

*** Significantly different from zero at the 1% level.

fertilization (Table 2), respectively. Yield response to N fertilization was statistically different among N sources at the 1% level (Table 4), which suggests that differences in the aforementioned optima are rather precise. The flatter yield responses to N fertilization for urea and UAN than for AN were likely caused by higher N volatilization of the urea-containing N sources (Howard et al.). Although the yield-maximizing N rates for urea and UAN were outside the range of the experimental data, the economic optima were within the range of the data as will be seen later. Yield responses to Glume-Blotch severity were not statistically different among N sources, whereas Take-All severity produced statistically different yield responses among N sources (Table 4).

Table 4. Pair-wise *F*-tests between Nitrogen Sources for the Nitrogen Rate, Glume-Blotch Severity, and Take-All Severity Coefficients of the Mean Wheat Yield Functions

Comparison	*F*-statistic[a]
Nitrogen[b]	
AN-Urea	4.34***
AN-UAN	4.99***
Urea-UAN	6.04***
Glume-Blotch[c]	
AN-Urea	1.30
AN-UAN	0.86
Urea-UAN	1.40
Take-All[d]	
AN-Urea	4.31***
AN-UAN	5.32***
Urea-UAN	6.23***

[a] *F*-statistics are calculated from ordinary least-squares results. Similar results were obtained from weighted least-squares results using the Wald statistic.

[b] *F*-statistics test the null hypothesis that the coefficients for N, N^2, $N \times G$, and $N \times TA$ are equal between N sources.

[c] *F*-statistics test the null hypothesis that the coefficients for G and $N \times G$ are equal between N sources.

[d] *F*-statistics test the null hypothesis that the coefficients for TA and $N \times TA$ are equal between N sources.

*** Significantly different from zero at the 1% level.

Yield Variances

Error sums of squares from the OLS mean yield functions and the accompanying *F*-statistics reported in Table 3 indicate that yield variances were not statistically different among N sources, all other factors being equal. This finding suggests that risk may not be a factor in the N-source decision when evaluated at the means of the data.

The estimated yield variance functions are presented in Table 5, and the marginal effects of the explanatory variables on yield variance evaluated at the means of the variables are presented in Table 6. The *F*-statistics and marginal effects indicate that N rate and Take-All severity increased yield variance for urea, that Glume-Blotch severity did not affect yield variance for any N source, and that none of the variables affected yield variances for AN and UAN. In addition, the pairwise *F*-tests in Table 7 indicate that Glume-Blotch severity did not affect yield variances differently among N sources (10% significance level). Although the effect of N rate on yield variance was statistically different from zero when urea

Table 5. Estimated Wheat Yield Variance Functions for Alternative Nitrogen Sources

Variable[a]	Nitrogen Source AN	 Urea	 UAN
Intercept	3.06*** (1.16)[b]	1.18 (0.83)	1.01 (0.96)
N	−0.008 (0.023)	0.04** (0.02)	−0.02 (0.02)
N^2	0.00001 (0.00013)	−0.0001 (0.0001)	−0.00001 (0.00011)
G	0.21 (0.21)	−0.07 (0.15)	−0.16 (0.17)
$N \times G$	−0.002 (0.002)	−0.002 (0.002)	0.0007 (0.0019)
TA	0.32 (0.22)	−0.19 (0.15)	−0.22 (0.18)
$N \times TA$	−0.002 (0.002)	0.005*** (0.002)	0.003 (0.002)
Adjusted R^2	−0.03	0.11	−0.02
n	90	89	90

[a] The dependent variable is the natural logarithm of the squared residuals from the respective mean wheat yield functions in Table 2; N is nitrogen applied (lb/acre); G is the natural logarithm of the Glume-Blotch rating from 0.01 to 10, with 0.01 being no disease present and 10 being the most severe disease rating; $N \times G$ is the interaction between N and G; TA is the natural logarithm of the Take-All rating from 0.01 to 10, with 0.01 being no disease present and 10 being the most severe disease rating; and $N \times TA$ is the interaction between N and TA.

[b] Numbers in parentheses are standard errors.

***, ** Significantly different from zero at the 1% and 5% levels, respectively.

was the N source, the N rate did not have statistically different effects on yield variances among N sources. Conversely, the effect of Take-All severity on yield variance for urea was statistically different from the effects on yield variances for AN and UAN. Results suggest that risk-averse wheat farmers may adjust the ranking of preferred N sources with higher levels of anticipated Take-All severity but that the N rate and Glume-Blotch severity may not be useful in differentiating among N sources for farmers with different levels of risk aversion.

Risk-Return Tradeoffs

Optimal N rates, wheat yields, net returns, and certainty equivalents for each N source under the assumptions of risk neutrality ($\lambda = 0$) and two level of risk aversion ($\lambda = 0.01$ and $\lambda = 0.02$) are presented in Table 8. When the disease variables (G and TA) were at their 3-yr. means (upper half of Table 8), the optimal N rate for a risk-neutral farmer was lowest for AN at 92 lb N/acre, compared with 147 and 126 lb N/acre for urea and UAN, respectively. AN had an optimal yield of 68 bu/acre—2 bu/acre less than the 70 bu/acre optimal yield for urea. Although AN produced a lower optimal yield, the lower N rate gave it the highest optimal net return of $209.14. AN was the optimal N sources for a net return–maximizing farmer, producing a $0.52/acre higher net return than the next best N source (urea) using 55.4 lb less N/acre. A lower optimal yield of 65 bu/acre gave UAN the lowest maximum net return of $193.61/acre—$15.53/acre less than the optimal net return for AN. Thus, a net-return–maximizing wheat farmer would rank the N sources as AN preferred to urea and urea preferred to UAN.

The larger affect of the N rate on yield variance for urea than for AN and UAN (Table 6) is manifested in the widening gap between CEs for AN and urea and the narrowing of the gap between CEs for urea and UAN. The CE gap between AN and urea increases from $0.52/acre to $9.94/acre, whereas the CE gap between urea and UAN narrows from $15.01/acre to $2.16/acre as λ increases from 0 to 0.02. As expected from the lack of statistically different marginal effects on yield variance for N rate (Table 7), increasing risk aversion did not affect the preference rankings of N sources when they were evaluated at the means of the variables. Thus, AN is the preferred N source, regardless of risk preferences.

Because the marginal effect of Take-All severity on yield variance was statistically significant for urea (Table 6) and the marginal

Table 6. Estimated Marginal Risk Effects of Nitrogen Rate, Glume-Blotch Severity, and Take-All Severity for Alternative Nitrogen Sources Evaluated at the Means of the Variables and Joint F-tests for Coefficients within Each Yield Variance Function

Comparison	Marginal Risk Effect	F-statistic
Nitrogen[a]		
AN	0.027	0.44
Urea	0.629	2.96**
UAN	−0.024	0.67
Glume-Blotch[b]		
AN	0.194	0.54
Urea	−4.532	0.84
UAN	−0.050	0.74
Take-All[c]		
AN	1.110	1.32
Urea	5.901	7.56***
UAN	0.003	1.12

[a] The marginal risk effect is the partial derivative of the exponential of the estimated wheat yield variance function (Table 5) with respect to N (nitrogen fertilization rate) evaluated at the means of the variables for a given N source. The F-statistic tests the null hypothesis that the coefficients for N, N^2, $N \times G$, and $N \times TA$ are jointly equal to zero for a given N source.

[b] The marginal risk effect is the partial derivative of the exponential of the estimated wheat yield variance function (Table 5) with respect to Glume-Blotch severity (Glume-Blotch Rating in Table 1) evaluated at the means of the variables for a given N source. The F-statistic tests the null hypothesis that the coefficients for G and $N \times G$ are jointly equal to zero for a given N source.

[c] The marginal risk effect is the partial derivative of the exponential of the estimated wheat yield variance function (Table 5) with respect to Take-All severity (Take-All Rating in Table 1) evaluated at the means of the variables for a given N source. The F-statistic tests the null hypothesis that the coefficients for TA and $N \times TA$ are jointly equal to zero for a given N source.

***, ** Significantly different from zero at the 1% and 5% levels, respectively.

Table 7. Pair-Wise F-tests between Nitrogen Sources for the Nitrogen Rate, Glume-Blotch, and Take-All Coefficients of the Wheat Yield Variance Functions

Comparison	F-statistic
Nitrogen[a]	
AN-Urea	1.75
AN-UAN	0.82
Urea-UAN	1.63
Glume-Blotch[b]	
AN-Urea	0.99
AN-UAN	1.18
Urea-UAN	1.17
Take-All[c]	
AN-Urea	3.09**
AN-UAN	2.11
Urea-UAN	3.01**

[a] F-statistics test the null hypothesis that the coefficients for N, N^2, $N \times G$, and $N \times TA$ are equal between N sources.

[b] F-statistics test the null hypothesis that the coefficients for G and $N \times G$ are equal between N sources.

[c] F-statistics test the null hypothesis that the coefficients for TA and $N \times TA$ are equal between N sources.

** Significantly different from zero at the 5% level.

effect for urea was statistically different from the marginal effects of Take-All severity for AN and UAN (Table 7), a question remains about whether the ranking of N sources would change if a farmer anticipated Take-All severity at the higher levels for 2000 that were found in the experiment. The lower half of Table 8 shows that, when Take-All severity is at its 2000 average level, AN is still the net-return and utility-maximizing N source. The risk neutral farmer who fertilizes with AN has a $35.58/acre advantage over the one who fertilizes with urea ($127.47–$91.89/acre) and a $41.90/acre advantage over the farmer who fertilizes with UAN. The preference ranking of N sources remains as before, with AN preferred to urea and urea preferred to UAN for the risk-neutral farmer. The ranking of N sources changes for risk-averse farmers in that UAN is preferred to urea when $\lambda = 0.01$ and 0.02. Regardless of the ranking of urea and UAN, AN is still the net-return and utility-maximizing N source. Thus, the decision to apply AN is robust over a wide range of risk preferences and disease severity levels.

Summary and Conclusions

We evaluated the mean yield and risk effects of alternative N sources and N rates for wheat production in the presence of the diseases Glume-Blotch and Take-All. A Just-Pope model was developed to analyze the risk ef-

Table 8. Risk-return Tradeoffs for Alternative Nitrogen Sources

	Coefficient of Absolute Risk Aversion		
Nitrogen Source	λ = 0.00	λ = 0.01	λ = 0.02
Variables at 3-year Mean[a]			
Ammonium Nitrate (AN)			
Nitrogen Fertilizer (lb/acre)	91.9	89.8	87.1
Wheat Yield (bu/acre)	67.9	67.8	67.5
Net Return ($/acre)	209.14	209.10	208.93
Certainty Equivalent ($/acre)	209.14	194.67	180.29
Urea			
Nitrogen Fertilizer (lb/acre)	147.3	140.6	128.2
Wheat Yield (bu/acre)	69.8	69.4	68.3
Net Return ($/acre)	208.62	208.46	207.37
Certainty Equivalent ($/acre)	208.62	189.26	170.35
Urea-Ammonium Nitrate (UAN)			
Nitrogen Fertilizer (lb/acre)	125.6	121.7	116.8
Wheat Yield (bu/acre)	64.9	64.6	64.2
Net Return ($/acre)	193.61	193.56	193.32
Certainty Equivalent ($/acre)	193.61	180.83	168.19
Take-All Rating at 2000 Mean[b]			
AN			
Nitrogen Fertilizer (lb/acre)	88.4	87.3	86.0
Wheat Yield (bu/acre)	43.9	43.8	43.7
Net Return ($/acre)	127.47	127.46	127.42
Certainty Equivalent ($/acre)	127.47	120.88	114.31
Urea			
Nitrogen Fertilizer (lb/acre)	102.9	74.6	61.9
Wheat Yield (bu/acre)	33.1	30.6	28.9
Net Return ($/acre)	91.89	89.14	86.12
Certainty Equivalent ($/acre)	91.89	81.47	74.99
UAN			
Nitrogen Fertilizer (lb/acre)	81.3	79.7	77.9
Wheat Yield (bu/acre)	30.4	30.3	30.2
Net Return ($/acre)	85.57	85.56	85.53
Certainty Equivalent ($/acre)	85.57	82.72	79.89

[a] Glume-Blotch and Take-All ratings at 3-year mean.

[b] Glume-Blotch rating at three-year mean and Take-All rating at 2000 mean.

fects of alternative N sources and to evaluate risk-return tradeoffs among N sources.

Our results suggest that (1) the marginal effects of N rate and Take-All severity on wheat yield variance were statistically significant for urea but not for AN and UAN; (2) Glume-Blotch severity did not have a significant marginal effect on yield variance for any N source; (3) AN required considerably less N fertilizer to achieve optimal yield than did urea and UAN, giving AN the highest optimal net return among the three N sources, even though yield was slightly lower than when urea was the N source; (4) risk-return tradeoffs suggest that the N rate had no effect on the utility-maximizing N source at different absolute risk aversion levels; and (5) anticipation of higher than average Take-All severity would make AN an even more attractive N source compared with urea or UAN.

The small effects in the experiment of the N fertilization rate on yield variances suggest that risk is not a significant factor in the N-fertilization decision. This finding is important to wheat farmers in West Tennessee and surrounding states with similar expected disease levels and growing conditions, because AN is the optimal N source under a wide variety of risk preferences and disease-severity levels; thus, wheat farmers can apply AN instead of urea or UAN with confidence. The estimated yield-response functions in this article indicate that wheat farmers in West Tennessee, or in other areas with similar conditions, would maximize net returns by fertilizing with AN at around 92 lb N/acre, whereas the optimal AN rate would decrease by only a small amount to 88 lb N/acre if the 2000 average Take-All severity level occurred. In addition, risk-averse farmers ($\lambda = 0.02$) would fertilize with only slightly less AN at around 86–87 lb N/acre.

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