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Variable Rate Nitrogen Application on Corn Fields: The Role of Spatial Variability and Weather

Roland K. Roberts, S. B. Mahajanashetti, Burton C. English,* James A. Larson, and Donald D. Tyler

ABSTRACT

Meta-response functions for corn yields and nitrogen losses were estimated from EPIC-generated data for three soil types and three weather scenarios. These metamodels were used to evaluate variable rate (VRT) versus uniform rate (URT) nitrogen application technologies for alternative weather scenarios and policy options. Except under very dry conditions, returns per acre for VRT were higher than for URT and the economic advantage of VRT increased as realized rainfall decreased from expected average rainfall. Nitrogen losses to the environment from VRT were lower for all situations examined, except on fields with little spatial variability.

Key Words: *Corn, environment, meta-response functions, nitrogen restriction, precision farming, site-specific management, spatial variability, weather variability.*

Precision farming addresses site-specific crop needs within a field. Its component technologies enable farmers to understand the changing plant-growth environment across a field, estimate input requirements for relatively homogeneous smaller-than-field-size units, and apply inputs on a site-specific basis. Claims are frequently made that precision farming enables farmers to enjoy greater economic benefits resulting from increased yields and/or reduced input use, while reducing the environmental harm associated with the excessive use of agricultural chemicals (Kitchen et al.; Koo and Williams; National Research Council; Sawyer; Watkins, Lu, and Huang).

Several studies (Babcock and Pautsch; Bongiovanni and Lowenberg-DeBoer; Bullock et al.; English, Roberts, and Mahajanashetti; Lowenberg-DeBoer; Lowenberg-DeBoer and Aghib; Roberts, English, and Mahajanashetti; Thrikawala et al.; Watkins, Lu, and Huang), along with several reviewed by Lowenberg-DeBoer and Swinton, have assessed the economic potential of variable rate input application technology (VRT). Profitability of VRT relative to uniform rate technology (URT) varies with the crop, the input, their prices, the cost of VRT relative to URT, the spatial distribution across a field of sub-field units (management zones), and the magnitudes of the yield response differences among management zones.

Roland K. Roberts and Burton C. English are professors, James A. Larson is associate professor, S.B. Mahajanashetti is a former graduate research assistant of the Department of Agricultural Economics and Donald D. Tyler is a professor of the Department of Plant and Soil Sciences, The University of Tennessee, Knoxville, TN. This article contributes to the objectives of Southern Regional Research Project S-283 and was supported by the University of Tennessee Agricultural Experiment Station. The authors acknowledge the contributions of the anonymous reviewers. * Corresponding author.

Most studies have ignored the effects of variable rate input application on the environment (Lowenberg-DeBoer; Swinton and Ahmed). Nevertheless, a few have addressed the potential impacts on environmental quality (e.g., Babcock and Pautsch, 1998; Thrikawala et al., 1999; Watkins et al., 1998). These studies showed the potential for VRT to improve net returns, reduce nitrogen usage, and positively impact groundwater quality.

The literature on precision farming also has largely ignored temporal yield variability (Lowenberg-DeBoer and Swinton). Fluctuating weather patterns can cause large variations in crop yields and farm profits. When crop-management decisions are based on weather expectations that are different from realized weather conditions, farm profits could be reduced.

The driving hypothesis behind this research was that VRT improves profits relative to URT and reduces negative environmental impacts resulting from unexpected weather conditions. These benefits would come through more efficient placement of inputs across management zones within a field. Another hypothesis was that the economic and environmental benefits of VRT are larger on fields with greater spatial variability. In the context of this study, spatial variability was defined by the proportions of a field in each management zone. A field is more spatially variable when its area is more evenly divided among management zones and less spatially variable when its area is more uniformly distributed in one management zone (English, Roberts, and Mahajanashetti; Roberts, English, and Mahajanashetti).

The objectives of this study were 1) to examine the economic feasibility of using VRT for nitrogen application on corn fields under alternative spatial variability and weather scenarios when expected and realized rainfall are the same and when they are different, 2) to test the hypothesis that VRT provides environmental benefits, and 3) to evaluate the economic and environmental effects of policies that subsidize the use of VRT or encourage VRT use by restricting nitrogen use on corn. These objectives were addressed for farmers faced with three possible rainfall scenarios making nitrogen application decisions on corn fields with differing amounts of spatial variability.

This paper examines differences in net revenue between VRT and URT when expected weather is different from realized weather. Risk would be an important element of a decision tool to help farmers make the VRT adoption decision if net revenues for these technologies were substantially different for different expected and realized weather conditions. The purpose of this research was to examine the magnitudes of these net revenue differences rather than to evaluate the effects of risk on the decision to adopt VRT.

Methods

Theoretical Model

Methods used in this study for economic analysis are similar to those of Roberts, English, and Mahajanashetti who evaluated fields with two management zones. Their methodology is extended to multiple management zones.

Optimal return above nitrogen cost per acre for a field using VRT (R^*_{VRT}) can be expressed as a profit function (Nicholson):

$$(1) \qquad R^*_{VRT} = \sum_{i}^{m} \lambda_i [P_c Y_i(N_i^*) - P_n N_i^*],$$

where λ_i is the proportion of the field in management zone i, such that $\Sigma_i^m{}_1 \lambda_i = 1$; P_c is the corn price (\$/bu); P_n is the nitrogen price (\$/lb); N_i^* is the economically optimal nitrogen rate applied to management zone i (lb/acre); and $Y_i(N_i^*)$ is corn yield (bu/acre) obtained from applying N_i^*. Alternatively, for URT the optimal return above nitrogen cost per acre for the field (R^*_{URT}) can be expressed as the following profit function:

$$(2) \qquad R^*_{URT} = P_c \sum_{i}^{m} \lambda_i Y_i(N^*_{FLD}) - P_n N^*_{FLD},$$

where λ_i is as defined in equation 1; N^*_{FLD} is the economically optimal uniform nitrogen application rate (lb/acre) obtained from a field average yield response function that is a weighted average of the parameters of the management-zone yield response functions, with the weights being the λ_is; and $Y_i(N^*_{FLD})$ is the corn yield (bu/acre) obtained from management zone i when N^*_{FLD} is applied. Optimal per-acre return to VRT ($\dot{R}VRT$) is given by the profit function:

$$(3) \qquad \dot{R}VRT = R^*_{VRT} - R^*_{URT}.$$

Given C as the additional cost per acre for VRT compared to URT, the economic criterion for VRT use on this field is $\dot{R}VRT \geq C$.

Spatial break-even variability proportions (SBVPs) (English, Roberts, and Mahajanashetti; Mahajanashetti; Roberts, English, and Mahajanashetti) for a particular management zone, say management zone m-1, are defined as the lower and upper limits of λ_{m-1} for given levels of $\lambda_1, \lambda_2, \ldots, \lambda_{m-2}$, P_c, P_n, and C such that $\dot{R}VRT = C$. The SBVPs for λ_m vary inversely with the SBVPs for λ_{m-1} because $\lambda_m = 1 - \lambda_{m-1} - \Sigma_1^{m-2}\lambda_i$. These SBVPs identify the boundaries of spatial variability between which the return from using VRT is greater than the cost of using it.

The optimal nitrogen fertilization rate using VRT or URT depends on yield response to nitrogen, which in turn depends on the amount of rainfall. If a farmer expected a given rainfall scenario to occur and it did occur, expected and realized yields would be the same; therefore, $\dot{R}VRT$ would equal realized field return to VRT. Alternatively, if the nitrogen application decision were based on an expected level of rainfall, but a different rainfall scenario occurred, expected and realized yields would be different because yield response to nitrogen would be different under the two rainfall scenarios. The sub-optimal realized return to VRT (RVRT) could be substantially different from the optimal $\dot{R}VRT$ that would occur when expected and realized rainfall are the same.

Data Generation and Response Function Estimation

Economic analysis of VRT versus URT requires estimates of $Y_i(N_i^*)$ and $Y_i(N^*_{FLD})$ (Snyder). For this study, yield response functions for three management zones were obtained by estimating metamodels (Law and Kelton) using data generated by the Environmental Policy Integrated Climate (EPIC) crop growth model (Benson) for three West Tennessee soil types suited to corn production (Mahajanashetti). A metamodel approximates the response surface of a simulation model, such as EPIC, using data generated by the simulation model (Law and Kelton).

EPIC is a daily time-step model. It simulates the growth of a pre-specified plant and its environment. Soil parameters such as organic matter, water holding capacity, and the amount of soil available for root support, change over time with changes is weather, input application, plant growth, and harvest.

EPIC was used to generate data for corn yields and nitrogen lost to leaching, surface runoff, and sub-surface flow. The data were generated for 20 years of simulations for each soil type assuming 29 nitrogen application rates ranging from 0 to 280 lb/acre in 10-lb increments. The modeled soils were deep Collins (0-percent slope with no fragipan), deep Memphis (1-percent slope with no fragipan), and Loring (3-percent slope with 30″ depth to fragipan). Reduced tillage practices were assumed for all three soils. These practices included chisel plowing and a single disking, leaving more than 30-percent residue cover after planting (Uri).

Monthly rainfall and temperature data recorded at the Covington Weather Station in West Tennessee (U.S. Department of Commerce) were used to create three weather scenarios for inclusion in the input data set of EPIC. Rainfall Scenario I used average rainfall amounts for each month over the 1988–1997 period, while Rainfall Scenarios II and III decreased the average rainfall amounts by 0.5 and 1.0 standard deviation, respectively. EPIC adjusted weather so the mean monthly minimum and maximum temperatures and the mean monthly precipitation for each simulation year were the same as the mean monthly values at the Covington Weather Station. Scenarios for above-average rainfall were not evaluated because, for these soils, simulated yields were neither improved nor restricted compared to Rainfall Scenario I. Under Rainfall Scenario I (mean of about 50 acre-inches/year), an average of 3.9 days was found where insufficient moisture caused plant stress. Decreasing the days of water stress through increased rainfall did not significantly impact yields.

Preliminary analysis of the data suggested that a quadratic-plus-plateau yield response model would best represent the data generated by EPIC. Furthermore, in several field experiments the quadratic-plus-plateau model better explained corn yield response to applied nitrogen than other models considered (Bullock and Bullock, 1994; Cerrato and Blackmer, 1990; Decker et al., 1994). The NLIN procedure (SAS Institute) was used to estimate nine quadratic-plus-plateau metamodels, one for each soil type and rainfall scenario as expressed in equation 4.

$$(4) \qquad \begin{aligned} Y &= \alpha + \beta N + \gamma N^2 && \text{if } N < N^c, \\ Y &= Y^p && \text{if } N \geq N^c, \end{aligned}$$

where Y is corn yield (bu/acre); N is the nitrogen fertilization rate (lb/acre); α, β and γ are parameters to be estimated by regression; and N^c and Y^p are the critical nitrogen rate and plateau yield, respectively.

Economic Analysis

Sixty-three fields, each having a different mix of soils, were analyzed. The λ_is were varied from 0 to 90 percent in 10-percent increments such that the sum of the percentages in the three soils equaled 100 percent and at least two soils existed in each field. For example, one field examined was assumed to be 0-percent Collins, 10-percent Memphis, and 90-percent Loring soils (0-10-90), while another field was assumed to be 20, 50, and 30-percent Collins, Memphis, and Loring soils (20-50-30), respectively. Weighted average yield response functions were calculated from the yield response functions estimated for each soil (equation 4) assuming the aforementioned soil mixes. Results were generated assuming that C was \$3.00/acre. This additional cost of VRT versus URT was close to the mean of \$3.08/acre found by Roberts, English, and Sleigh in a survey of firms that provided precision farming services to Tennessee farmers. The season average price received by farmers for corn (P_C) of \$2.79/bu and the annual average urea price (P_n) of \$0.26/lb of nitrogen, averaged over the 1993–1997 period (Tennessee Department of Agriculture), were used in calculating the economic optima (N_i^* and N_{FLD}^*).

The first part of Objective 1 was accomplished by assuming the producer made optimal nitrogen decisions based on the yield response functions for Rainfall Scenario I and that the amounts of precipitation assumed for Rainfall Scenario I were realized. The second part of Objective 1 was accomplished by assuming that the yield response functions for Rainfall Scenario I were used to make optimal nitrogen decisions, but that the amounts of precipitation and corresponding yield response functions estimated for Rainfall Scenarios II or III were realized.

Environmental Analysis

With higher nitrogen fertilization rates comes greater potential for nitrogen loss to the environment. Following Chowdhury and Lacewell and Wu, Laxminarayan, and Babcock, environmental data generated with EPIC were synthesized into functional relationships. As in Wu, Laxminarayan, and Babcock, the nitrogen loss functions were estimated with ordinary least squares (SAS Institute) as a linear function of the amount of nitrogen applied as follows:

$$(5) \qquad NL_i = a + bN_i,$$

where i = 1 for Collins, 2 for Memphis, and 3 for Lorings soils; NL is nitrogen lost to the environment through leaching, surface runoff, and sub-surface flow (lb/acre); N is the nitrogen fertilization rate (lb/acre), and a and b are estimated parameters. These functions were used to predict nitrogen loss resulting from the profit-maximizing behavior of farmers under VRT and URT. The second objective was accomplished by calculating the amount of nitrogen lost to the environment per acre as the weighted sum (weighted by the λ_is) of nitrogen loss for each soil series as indicated by output from EPIC. Further, the nitrogen loss difference (NLD), defined as nitrogen loss with VRT minus nitrogen loss with URT, and the nitrogen applied difference (NAD), defined as the amount of nitrogen applied using VRT less the amount of nitrogen applied using URT, were calculated for each field. The NLD was used as an indicator of the impact on the environment of adopting VRT.

The N coefficients in equation 5 are important for this analysis because they are the marginal effects of applied fertilizer nitrogen on nitrogen loss. Of particular importance are the relative magnitudes of these N coefficients because they determine nitrogen loss for VRT relative to URT. The magnitudes of the N coefficients depend on how crop yields respond to rainfall. Generally speaking, less rainfall is associated with less nitrogen lost to the environment because water is required for nitrogen leaching, runoff, and sub-surface flow. This effect would reduce the N coefficients as rainfall declines from Rainfall Scenario I to Rainfall Scenario III. Conversely, reduced rainfall usually means lower yields and less plant uptake, making more of the applied nitrogen available for potential loss. This effect would increase the N coefficients as rainfall declines. Holding rainfall constant, with its rooting-zone restriction the Loring soil was expected to produce the lowest yields among the three soils; therefore, it was expected to have the largest N coefficients. For the same reason yield reductions associated with decreased rainfall were expected to be greatest for the Loring soil; thus, the N coefficients for Loring soil were expected to increase relative to the other soils in going from Rainfall Scenario I to Rainfall Scenario III.

Policy Options

If VRT promises environmental benefits by reducing nitrogen lost to the environment compared to URT, but farmers hesitate to adopt the technology fearing economic losses, policymakers may want to consider policy options that would induce farmers to adopt VRT. Policy options that subsidize the cost of using VRT or restrict the application of nitrogen are considered in this study.

Farmers who find $\dot{R}VRT < C$ might adopt VRT if C could be reduced enough through a subsidy. The amount of the required subsidy depends on the difference between $\dot{R}VRT$ and C. The level of $\dot{R}VRT$ depends on spatial variability, differences in yield response functions among soil types, and input and product prices. The amount of subsidy varies in this study from field to field because of differences in spatial variability across fields.

If nitrogen application were restricted, farmers using VRT would apply each unit of nitrogen based on its marginal value, whereas farmers using URT would apply the input uniformly not accounting for differences in marginal values among soil types. The URT amount of nitrogen applied would no longer be economically optimal for the weighted average response function, causing the return above nitrogen cost for VRT to change relative to URT. As a result, farmers may have an economic incentive to adopt VRT on fields where URT was used in the unconstrained case. The first nitrogen-restriction policy evaluated in this study was to constrain nitrogen application to 95 percent of its URT rate.[1] A new per-acre net return above nitrogen cost ($\tilde{R}_{URT}$) for URT was determined by replacing N^*_{FLD} in the average response function with 0.95 N^*_{FLD}.

Several steps were required to determine nitrogen levels for VRT under the constrained nitrogen policy. First, the amount of nitrogen allowed under URT (95 N^*_{FLD}) was compared to the weighted sum across soil types of the unconstrained nitrogen levels under VRT. If this sum was less than the URT constrained level, the optimal values for VRT were used. If the sum of the optimal VRT rates required more fertilizer than the restricted URT rate, N^*_i was reduced by equating the marginal physical products of the three soils given that

[1] The authors selected 95 percent of the URT rate to illustrate potential impacts. The percentage reduction could be larger or smaller under a specific policy.

Table 1. Estimated Corn Yield Response Functions for Applied Nitrogen for Collins, Memphis, and Loring Soils under Three Rainfall Scenarios

Soil/Rainfall Scenario	Equation[a]	
Collins		
Rainfall Scenario I	$Y = 14.415 + 1.685N - 0.0038N^2$	if $N < 221.71$
	(2.963)[b] (0.065) (0.0003)	
	$Y = 201.21$	if $N \geq 221.71$
Rainfall Scenario II	$Y = 14.341 + 1.674N - 0.0035N^2$	if $N < 236.44$
	(3.101) (0.063) (0.0003)	
	$Y = 212.24$	if $N \geq 236.44$
Rainfall Scenario III	$Y = 14.065 + 1.717N - 0.0055N^2$	if $N < 155.24$
	(2.906) (0.090) (0.0006)	
	$Y = 147.34$	if $N \geq 155.24$
Memphis		
Rainfall Scenario I	$Y = 15.297 + 1.68N - 0.0038N^2$	if $N < 220.477$
	(2.862) (0.063) (0.0003)	
	$Y = 200.49$	if $N \geq 220.47$
Rainfall Scenario II	$Y = 12.404 + 1.729N - 0.0039N^2$	if $N < 223.96$
	(3.206) (0.068) (0.0003)	
	$Y = 206.02$	if $N \geq 223.96$
Rainfall Scenario III	$Y = 17.094 + 1.704N - 0.0048N^2$	if $N < 177.13$
	(3.702) (0.101) (0.0006)	
	$Y = 168.01$	if $N \geq 177.13$
Loring		
Rainfall Scenario I	$Y = 2.356 + 1.533N - 0.0043N^2$	if $N < 180.44$
	(2.493) (0.064) (0.0003)	
	$Y = 140.60$	if $N \geq 180.44$
Rainfall Scenario II	$Y = 7.363 + 1.357N - 0.0056N^2$	if $N < 121.16$
	(3.883) (0.165) (0.00133)	
	$Y = 89.57$	if $N \geq 121.16$
Rainfall Scenario III	$Y = 10.166 + 0.521N - 0.0040N^2$	if $N < 64.80$
	(0.703) (0.055) (0.0009)	
	$Y = 27.05$	if $N \geq 64.80$

[a] Y is corn yield in bushels per acre and N is nitrogen in pounds per acre.
[b] Numbers in parentheses are asymptotic standard errors.

the total amount of nitrogen applied with VRT equaled 0.95 N^*_{FLD}. Once the nitrogen rates under the nitrogen-restriction policy were determined, yields and $\tilde{R}_{VRT}$ were estimated. Referring to $\tilde{R}_{VRT} - \tilde{R}_{URT}$ as the constrained return to VRT ($R\tilde{V}RT$), the necessary economic condition for VRT adoption becomes $R\tilde{V}RT \geq C$. Farmers who found URT more beneficial on a field in the unconstrained case could find VRT more profitable under the nitrogen-restriction policy.

A second nitrogen-restriction policy evaluated changes in $R\tilde{V}RT$ and NAD when NLD was required to be zero for each field. The NLDs were forced to be zero by reducing nitrogen loss for URT to the level for VRT.

Results

Estimated Response functions

Table 1 presents the estimated corn yield response functions for Collins, Memphis and Loring soils under Rainfall Scenarios I, II, and III. The linear and quadratic coefficients for all equations had the expected signs and the asymptotic standard errors were low relative to the magnitudes of the coefficients.

The response functions for both Collins and Memphis soils changed little between Rainfall Scenarios I and II, suggesting that the lower rainfall associated with Rainfall Scenario II did not reduce yields substantially on these soils. Alternatively, the lower moisture associated with Rainfall Scenario III lowered corn yields relative to Rainfall Scenarios I and II as reflected in more negative quadratic coefficients in the response functions and lower plateau yields.

The linear and quadratic coefficients of the yield response functions and the yield plateaus suggest that yields were lower at each nitrogen fertilization rate for the shallow Loring soil than for the deep Collins and Memphis soils. In addition, yields for the Loring soil were reduced for Rainfall Scenario II relative to Rainfall Scenario I and reduced substantially more for Rainfall Scenario III. As expected, these yield reductions were considerably greater than the yield reductions for the Collins and Memphis soils.

The yield estimates provided by EPIC were higher than county average yields observed in the West Tennessee region, which range from 110 to 135 bushels per acre (Tennessee Department of Agriculture). The Rainfall Scenario I yield plateaus estimated for all three soils exceeded these averages. However, the yield estimates provided by EPIC did not specifically account for many yield-inhibiting factors that reduce county average corn yields; for example, species competition, pockets of poor drainage, and poor farm management. Also, the analysis did not account for other less-productive soils in the region that are used for corn production. After reviewing the EPIC output, the authors believe that the yield-nitrogen response reflected in the EPIC data was similar to the expected response for these soils. However, in comparing the EPIC data to other data series, the yield plateau for the Memphis soil probably should be lower for most situations. The Memphis soil assumed for this analysis was extremely well drained with a deep rooting zone. On the other hand, because of its shallow rooting zone, the corn production capacity of the Loring soil is greatly diminished without adequate rainfall. As expected, the Loring soil performed poorly under drought conditions in the EPIC simulations.

The estimated nitrogen loss functions (Table 2) had intercepts that were close to zero and most were not significantly different from zero, suggesting that little nitrogen carry-over existed from year to year for these Loess derived soils. The applied fertilizer nitrogen (N) coefficients were all positive and significantly different from zero as expected. For the deep Collins and Memphis soils, the effect on nitrogen loss from reduced water flow outweighed the effect from reduced plant uptake causing the N coefficients to decline from Rainfall Scenario I to Rainfall Scenario III. For the shallow Loring soil the N coefficients are much larger than for the other soils because of less plant uptake associated with lower yields at each nitrogen fertilization rate (Table 1). Also, the N coefficients for the Loring soil increased with reduced rainfall because yields and plant uptake declined substantially, offsetting the effect of reduced water flow.

Expected Rainfall Equals Realized Rainfall

When farmers expected average rainfall and average rainfall occurred, $\dot{R}VRT$ was greater than C for 22 of 63 fields (Table 3). The lower and upper SBVPs for Memphis and Loring soils, given different proportions of the field in Collins soil are reported in Table 4. When a field was 70 percent or more Collins soil, $\dot{R}VRT$ was not greater than C for any combination of Memphis and Loring soils (Table 3, fields 55–63; Table 4, row headed 70). As Collins soil increased from 0 to 60 percent, the lower SBVPs for Loring soil decreased only slightly from 33 to 31 percent, while the upper SBVPs for Memphis soil decreased substantially (Table 4). Furthermore, when a field contained only Collins and Memphis soils in any proportions (Table 3, fields 19, 28, 36, 43, 49, 54, 58, 61, and 63), $\dot{R}VRT$ was estimated at zero. Also, given a positive percentage of a field in Loring soil, variation in the proportions of Collins and Memphis soils changed $\dot{R}VRT$ only slightly (eg., Table 3, fields 8, 17, 26, 34, 41, 47, 52, 56, and 59). These findings

Table 2. Estimated Nitrogen Loss Response Functions for Collins, Memphis, and Loring Soils under Three Rainfall Scenarios

Soil/Rainfall Scenario	Variable	Coefficient	Standard Error
Collins			
Rainfall I	Intercept	4.2960*[a]	0.7828
	N[b]	0.0321*	0.0037
	R^2	0.9380	
Rainfall II	Intercept	1.8010*	0.6987
	N	0.0185*	0.0033
	R^2	0.8620	
Rainfall III	Intercept	0.4610	0.5946
	N	0.0175*	0.0028
	R^2	0.8860	
Memphis			
Rainfall I	Intercept	1.9540	1.4483
	N	0.0474*	0.0068
	R^2	0.9060	
Rainfall II	Intercept	0.8140	1.1602
	N	0.0242*	0.0055
	R^2	0.7960	
Rainfall III	Intercept	−0.3540	0.4199
	N	0.0170*	0.0020
	R^2	0.9360	
Loring			
Rainfall I	Intercept	−7.1440	16.4848
	N	0.4220*	0.0779
	R^2	0.8550	
Rainfall II	Intercept	−6.7810	11.8105
	N	0.4460*	0.0558
	R^2	0.9270	
Rainfall III	Intercept	−5.2090	13.0888
	N	0.6020*	0.0618
	R^2	0.9500	

[a] * Significant at the $\alpha = 0.05$ level.
[b] N is applied nitrogen in pounds per acre.

flow from the similarity in the marginal physical products of the Collins and Memphis yield response functions in Table 1. Results suggest that fields containing these three soil types have two rather than three management zones, one being a combination of Collins and Memphis soils and the other containing Loring soil.

The lower SBVPs for Loring soil (Table 4) indicate that fields had to contain more than 31 to 33 percent Loring soil for RVRT to be greater than C (Table 3, compare fields 6–7, 15–16, 24–25, 32–33, 39–40, 45–46 and 50–51, and see field 55). The lower SBVPs for Memphis soil added to the percentage of Collins soil in the row headings of Table 4 indicate that fields had to contain more than 22 to 24 percent Collins and/or Memphis soils for VRT to be more profitable than URT. The upper SBVPs for Memphis soil added to the percentage of Collins soil in the row headings of Table 4 indicate that a field had to contain less than 67 to 69 percent Collins and/or Memphis soils for VRT to be more profitable than URT.

Results in Table 3 show that VRT required larger amounts of fertilizer nitrogen per acre than URT as indicated by positive NADs. The exceptions occurred in fields with only Collins and Memphis soils, which had NADs of zero.

Table 3. Return to Variable Rate Technology, Nitrogen Application Difference, and Nitrogen Loss Difference for 63 Hypothetical Corn Fields when Rainfall Scenario I was Expected and Realized

Field Number	Soil Mix[a]	RV̇RT[b]	NAD[b]	NLD[b]	Field Number	Soil Mix	RV̇RT	NAD	NLD
		$/acre	lb/acre	lb/acre			$/acre	lb/acre	lb/acre
1	0-10-90	**1.46**[c]	0.37	−1.17	32	30-30-40	3.59	1.06	−3.42
2	0-20-80	**2.62**	0.66	−2.10	33	30-40-30	**2.86**	0.93	−3.01
3	0-30-70	3.48	0.87	−2.79	34	30-50-20	**1.94**	0.72	−2.31
4	0-40-60	3.93	1.01	−3.22	35	30-60-10	**0.95**	0.41	−1.31
5	0-50-50	3.91	1.06	−3.39	36	30-70-0	**0.00**	0.00	0.00
6	0-60-40	3.50	1.03	−3.29	37	40-0-60	4.15	0.06	−3.47
7	0-70-30	**2.80**	0.91	−2.91	38	40-10-50	4.08	1.11	−3.60
8	0-80-20	**1.91**	0.70	−2.24	39	40-20-40	3.62	1.07	−3.46
9	0-90-10	**0.93**	0.40	−1.28	40	40-30-30	**2.88**	0.94	−3.04
10	10-0-90	**1.55**	0.39	−1.26	41	40-40-20	**1.95**	0.72	−2.33
11	10-10-80	**2.70**	0.68	−2.18	42	40-50-10	**0.95**	0.41	−1.32
12	10-20-70	3.55	0.89	−2.86	43	40-60-0	**0.00**	0.00	0.00
13	10-30-60	3.98	1.02	−3.28	44	50-0-50	4.12	1.12	−3.65
14	10-40-50	3.95	1.07	−3.44	45	50-10-40	3.65	1.08	−3.50
15	10-50-40	3.53	1.04	−3.34	46	50-20-30	**2.90**	0.95	−3.08
16	10-60-30	**2.82**	0.92	−2.95	47	50-30-20	**1.96**	0.73	−2.36
17	10-70-20	**1.92**	0.71	−2.27	48	50-40-10	**0.96**	0.41	−1.34
18	10-80-10	**0.94**	0.40	−1.29	49	50-50-0	**0.00**	0.00	0.00
19	10-90-0	**0.00**	0.00	0.00	50	60-0-40	3.68	1.09	−3.55
20	20-0-80	**2.78**	0.69	−2.26	51	60-10-30	**2.92**	0.95	−3.11
21	20-10-70	3.62	0.90	−2.93	52	60-20-20	**1.97**	0.73	−2.38
22	20-20-60	4.04	1.04	−3.35	53	60-30-10	**0.96**	0.41	−1.35
23	20-30-50	3.99	1.08	−3.50	54	60-40-0	**0.00**	0.00	0.00
24	20-40-40	3.56	1.05	−3.38	55	70-0-30	**2.93**	0.96	−3.14
25	20-50-30	**2.84**	0.93	−2.98	56	70-10-20	**1.98**	0.74	−2.40
26	20-60-20	**1.93**	0.71	−2.29	57	70-20-10	**0.96**	0.42	−1.36
27	20-70-10	**0.94**	0.40	−1.30	58	70-30-0	**0.00**	0.00	0.00
28	20-80-0	**0.00**	0.00	0.00	59	80-0-20	**1.99**	0.74	−2.42
29	30-0-70	3.69	0.92	−3.00	60	80-10-10	**0.97**	0.42	−1.37
30	30-10-60	4.09	1.05	−3.41	61	80-20-0	**0.00**	0.00	0.00
31	30-20-50	4.03	1.10	−3.55	62	90-0-10	**0.97**	0.42	−1.38
					63	90-10-0	**0.00**	0.00	0.00

[a] Percentages of the field in Collins, Memphis, and Loring soils, respectively.
[b] Note: Abbreviations used in this table include RV̇RT (Return to Variable Rate Technology), NAD (Nitrogen Application Difference), and NLD (Nitrogen Loss Difference).
[c] RV̇RTs less than the custom charge ($3.00/acre) are shown in bold.

Furthermore, the NADs increased with the proportion of a field in Loring soil up to 60 percent Loring soil and declined thereafter.

The NADs were higher for VRT than for URT because of differences in the marginal physical products of the Loring versus the Collins and Memphis soils in going from the field average optimal nitrogen rate to the optimal nitrogen rates for each soil. Using Field 23 (20-30-50) as an example (Table 3), the optimal nitrogen rate for the field average function was 187.97 lb/acre while the optimal rates for the Collins, Memphis, and Loring soils were 209.45, 208.24, and 169.39 lb/acre, respectively. Subtracting these optimal rates from the field average optimal rate gives an increase in nitrogen use of 21.48 and 20.27 lb/acre for Collins and Memphis soils, respec-

Table 4. Spatial Break-even Variability Proportions[a] for Memphis and Loring Soils for Specified Proportions of a Field in Collins Soil when Rainfall Scenario I was Expected and Rainfall Scenarios I or II were Realized

	Rainfall Scenario I Realized				Rainfall Scenario II Realized			
	Memphis		Loring		Memphis		Loring	
Collins	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
	% of field							
0	24	67	33	76	13	78	22	87
10	13	58	32	77	0[b]	69	21	90[c]
20	2	48	32	78	0[b]	61	19	80[c]
30	0[b]	38	32	70[c]	0[b]	52	18	70[c]
40	0[b]	29	31	60[c]	0[b]	43	17	60[c]
50	0[b]	19	31	50[c]	0[b]	34	16	50[c]
60	0[b]	9	31	40[c]	0[b]	25	16	40[c]
70	[d]	[d]	[d]	[d]	0[b]	15	15	30[c]
80	[d]	[d]	[d]	[d]	0[b]	6	14	20[c]
90	[d]	[d]	[d]	[d]	[d]	[d]	[d]	[d]

[a] Spatial Break-even Variability Proportions (SBVP) can be estimated for the percentages of a field in any two management zones such that the $\dot{R}VRT$ (Return to Variable Rate Technology) is equal to C (cost of using that technology) (English, Roberts, and Mahajanashetti; Roberts, English, and Mahajanashetti). The SBVPs in this table are calculated assuming the percentage of a field in Collins soil is fixed at the levels in the first column.
[b] No lower SBVP exists because when Memphis soil reaches its minimum allowable percentage of zero, the $\dot{R}VRT > C$.
[c] No upper SBVP exists because when Loring soil reaches its maximum allowable percentage, the $\dot{R}VRT > C$.
[d] No SBVP exists because for this percentage of Collins soil all possible combinations of Memphis and Loring soils give the $\dot{R}VRT < C$.

tively, and a decrease in nitrogen use of 18.58 lb/acre for the Loring soil. Weighting these changes by the proportions of the field in each soil gives a field average increase in nitrogen use for VRT compared to URT of 1.08 lb/acre.

Even though more nitrogen was applied with VRT than with URT, less nitrogen was lost to the environment (NLD), indicating that the VRT nitrogen rates were more in line with efficient crop production. In addition, the shallow Loring soil was more susceptible to nitrogen loss than were the Collins and Memphis soils as reflected in the N coefficients in Table 2. Those coefficients indicate that a larger portion of the change in applied nitrogen, in going from URT to VRT, was lost to the environment for the Loring soil (0.422 lb lost/lb applied/acre) than for the Collins (0.0321 lb lost/lb applied/acre) and Memphis (0.0474 lb lost/lb applied/acre) soils.

Results suggest that the amount of nitrogen lost to the environment could be reduced between two and four lb/acre by profit-maximizing farmers who adopt VRT, with the greatest benefit occurring on fields with around 50 percent Loring soil regardless of the percentages of a field in Collins and Memphis soils. In addition, nitrogen lost to the environment could be reduced by about two or three lb/acre by farmers with marginal fields (Fields 2, 7, 11, 16, 20, 25, 33, 40, 46, 51, and 55) if they could be induced to adopt VRT.

Expected Rainfall Not Equal Realized Rainfall

Table 5 presents the results when farmers make decisions based on Rainfall Scenario I response functions, but the response functions for Rainfall Scenario II are realized. Patterns in RVRT and NLD were similar to those reported when average rainfall was expected and realized (Table 3). In this case, however, the lower SBVPs for Loring soil (Table 4) varied slightly more (ranging between 14 and 22 percent) than when Rainfall Scenario I was realized, reflecting more divergent yield response functions for Collins and Memphis soils (Ta-

Table 5. Return to Variable Rate Technology and Nitrogen Loss Difference for 63 Hypothetical Corn Fields when Rainfall Scenario I was Expected and Rainfall Scenario II was Realized

Field Number	Soil Mix[a]	RVRT[b]	NLD[b]	Field Number	Soil Mix	RVRT	NLD
		$/acre	lb/acre			$/acre	lb/acre
1	0-10-90	**2.45**[c]	−1.33	32	30-30-40	5.92	−3.82
2	0-20-80	4.15[d]	−2.38	33	30-40-30	4.74[d]	−3.37
3	0-30-70	5.17	−3.16	34	30-50-20	3.30[d]	−2.59
4	0-40-60	5.58	−3.65	35	30-60-10	**1.69**	−1.47
5	0-50-50	5.45	−3.84	36	30-70-0	**0.05**	0.00
6	0-60-40	4.87	−3.73	37	40-0-60	7.57	−3.81
7	0-70-30	3.93[d]	−3.30	38	40-10-50	7.14	−3.98
8	0-80-20	**2.73**	−2.54	39	40-20-40	6.26	−3.84
9	0-90-10	**1.38**	−1.45	40	40-30-30	5.00[d]	−3.39
10	10-0-90	3.15[d]	−1.38	41	40-40-20	3.47[d]	−2.60
11	10-10-80	4.79[d]	−2.44	42	40-50-10	**1.79**	−1.48
12	10-20-70	5.74	−3.21	43	40-60-0	**0.06**	0.00
13	10-30-60	6.08	−3.69	44	50-0-50	7.56	−4.02
14	10-40-50	5.88	−3.88	45	50-10-40	6.59	−3.87
15	10-50-40	5.23	−3.76	46	50-20-30	5.26[d]	−3.41
16	10-60-30	4.21[d]	−3.32	47	50-30-20	3.65[d]	−2.62
17	10-70-20	**2.92**	−2.56	48	50-40-10	**1.88**	−1.49
18	10-80-10	**1.49**	−1.46	49	50-50-0	**0.06**	0.00
19	10-90-0	**0.02**	0.00	50	60-0-40	6.93	−3.90
20	20-0-80	5.43[d]	−2.49	51	60-10-30	5.51[d]	−3.43
21	20-10-70	6.31	−3.25	52	60-20-20	3.82[d]	−2.63
22	20-20-60	6.58	−3.73	53	60-30-10	**1.96**	−1.49
23	20-30-50	6.31	−3.91	54	60-40-0	**0.06**	0.00
24	20-40-40	5.57	−3.79	55	70-0-30	5.76[d]	−3.45
25	20-50-30	4.48[d]	−3.34	56	70-10-20	3.99[d]	−2.65
26	20-60-20	3.11[d]	−2.57	57	70-20-10	**2.04**	−1.50
27	20-70-10	**1.59**	−1.46	58	70-30-0	**0.05**	0.00
28	20-80-0	**0.04**	0.00	59	80-0-20	4.15[d]	−2.66
29	30-0-70	6.88[d]	−3.30	60	80-10-10	**2.12**	−1.51
30	30-10-60	7.07	−3.77	61	80-20-0	**0.04**	0.00
31	30-20-50	6.73	−3.95	62	90-0-10	**2.19**	−1.51
				63	90-10-0	**0.02**	0.00

[a] Percentages of the field in Collins, Memphis, and Loring soils, respectively.
[b] RVRT is the (Return to Variable Rate Technology) and NLD is the (Nitrogen Loss Difference).
[c] RVRTs less than custom charges ($3.00/acre) are shown in bold.
[d] RVRTs were less than $3.00/acre in Table 3 but are greater than $3.00/acre in this case.

ble 1). Without exception the magnitudes of the RVRTs were higher than when average rainfall was expected and realized (Table 5). The higher RVRTs caused the lower and upper SBVPs for Loring soil to move farther apart (Table 4). For example, the lower and upper SBVPs for Loring soil when Collins soil was not included in a field (Table 4, row headed 0) were estimated at 22 and 87 percent, respectively. These SBVPs were substantially farther apart than the 33 and 76 percent SBVPs estimated when Scenario I was expected and realized. Thus, for RVRT ≥ C, a field could be more uniformly Loring soil (87 percent) than when expected and realized rainfall were the same (76 percent). This change in SBVPs indicates that wrong weather expectations, compared to correct ones, resulted in

Table 6. Return to Variable Rate Technology and Nitrogen Loss Difference for 63 Hypothetical Corn Fields when Rainfall Scenario I was Expected and Rainfall Scenario III Realized

Field Number	Soil Mix[a]	RVRT[b]	NLD[b]	Field Number	Soil Mix	RVRT	NLD
		$/acre	lb/acre			$/acre	lb/acre
1	0-10-90	−0.07	−1.85	32	30-30-40	−0.28	−5.27
2	0-20-80	−0.17	−3.32	33	30-40-30	−0.24	−4.65
3	0-30-70	−0.23	−4.40	34	30-50-20	−0.19	−3.58
4	0-40-60	−0.26	−5.08	35	30-60-10	−0.11	−2.03
5	0-50-50	−0.28	−5.35	36	30-70-0	0.00	0.00
6	0-60-40	−0.27	−5.19	37	40-0-60	−0.28	−5.22
7	0-70-30	−0.24	−4.59	38	40-10-50	−0.29	−5.47
8	0-80-20	−0.18	−3.54	39	40-20-40	−0.28	−5.29
9	0-90-10	−0.10	−2.01	40	40-30-30	−0.24	−4.67
10	10-0-90	−0.10	−1.90	41	40-40-20	−0.19	−3.59
11	10-10-80	−0.18	−3.36	42	40-50-10	−0.11	−2.04
12	10-20-70	−0.23	−4.44	43	40-60-0	0.00	0.00
13	10-30-60	−0.27	−5.12	44	50-0-50	−0.29	−5.50
14	10-40-50	−0.28	−5.38	45	50-10-40	−0.28	−5.32
15	10-50-40	−0.27	−5.22	46	50-20-30	−0.25	−4.69
16	10-60-30	−0.24	−4.61	47	50-30-20	−0.19	−3.60
17	10-70-20	−0.18	−3.55	48	50-40-10	−0.11	−2.05
18	10-80-10	−0.10	−2.02	49	50-50-0	0.00	0.00
19	10-90-0	0.00	0.00	50	60-0-40	−0.28	−5.34
20	20-0-80	−0.18	−3.41	51	60-10-30	−0.25	−4.71
21	20-10-70	−0.24	−4.48	52	60-20-20	−0.19	−3.62
22	20-20-60	−0.27	−5.15	53	60-30-10	−0.11	−2.05
23	20-30-50	−0.28	−5.41	54	60-40-0	0.00	0.00
24	20-40-40	−0.27	−5.24	55	70-0-30	−0.25	−4.73
25	20-50-30	−0.24	−4.63	56	70-10-20	−0.19	−3.63
26	20-60-20	−0.19	−3.57	57	70-20-10	−0.11	−2.06
27	20-70-10	−0.11	−2.03	58	70-30-0	0.00	0.00
28	20-80-0	0.00	0.00	59	80-0-20	−0.19	−3.64
29	30-0-70	−0.24	−4.52	60	80-10-10	−0.11	−2.07
30	30-10-60	−0.27	−5.19	61	80-20-0	0.00	0.00
31	30-20-50	−0.29	−5.44	62	90-0-10	−0.11	−2.07
				63	90-10-0	0.00	0.00

[a] Percentages of the field in Collins, Memphis, and Loring soils, respectively.
[b] RVRT is the (Return to Variable Rate Technology) and NLD is the (Nitrogen Loss Difference).

less spatial variability being required for VRT to be more profitable than URT.

The NLDs in Table 5 are more negative than those in Table 3, suggesting that even less nitrogen was lost to the environment with VRT compared to URT when decisions were based on Rainfall Scenario I response functions and Rainfall Scenario II response functions were realized. These larger differences occurred because the marginal physical products for Collins and Memphis soils changed little between Rainfall Scenarios I and II, while the marginal physical product for Loring soil declined substantially between these two scenarios (Table 1). Although the NADs were the same as when Rainfall Scenario I was expected and realized, the NLDs indicate that VRT was more efficient in using fertilizer nitrogen and increasing yields relative to URT when Rainfall Scenario II was realized.

Table 6 presents the results when Rainfall Scenario I was expected and Rainfall Scenario

III was realized. Under these conditions, the RVRTs were negative except when a field had 0 percent Loring soil. Negative RVRTs resulted because optimal nitrogen rates for Rainfall Scenario I for both URT and VRT were on the yield plateaus of the Rainfall Scenario III yield response functions for each of the three soils. In other words, changes in nitrogen levels from URT to VRT did not affect yields, but differences in nitrogen costs were affected. (See positive NADs in Table 3.) For example, the NAD for Field 23 (20-30-50) was 1.08 lb/acre (Table 3). Multiplying this NAD by the price of nitrogen ($0.26/lb) gives an additional nitrogen cost for VRT compared to URT of $0.28/acre, which is equivalent in absolute value to the RVRT of −$0.28 for Field 23 in Table 6. Thus because of lower yield responses under Rainfall Scenario III, a farmer who planned based on Rainfall Scenario I and used VRT would reduce profits or increase losses relative to URT by the $3.00/acre cost of using VRT plus the cost of using more fertilizer nitrogen compared to URT. No SBVPs existed when plans were based on Rainfall Scenario I and Rainfall Scenario III was realized because RVRT < C for all levels of the λ_is.

The environment would benefit from using VRT instead of URT when Rainfall Scenario I is expected and Rainfall Scenario III is realized as indicated by negative NLDs (Table 6). In some fields that were between 30 and 70 percent Loring soil, results indicate that over five lb/acre less nitrogen would be lost to the environment with VRT than with URT. The NLDs for this situation were more negative than when Rainfall Scenario I was expected and Rainfall Scenarios I and II were realized. In fact, these results indicate that for decisions based on average rainfall the lower the amount of realized rainfall, the greater the environmental benefit from using VRT rather than URT.

Policies to Promote VRT Adoption

Given that Rainfall Scenario I was expected and realized, if profit-maximizing farmers with marginal fields (Fields 2, 7, 11, 16, 20, 25, 33, 40, 46, 51, and 55) could be induced to use VRT through a subsidy, the environmental benefits indicated by the negative NLDs in Table 3 could be achieved. The subsidy required to provide farmers of these fields with the economic incentive to adopt VRT ranged from $0.38/acre for Field 2 (0-20-80) to $0.07/acre for Field 55 (70-0-30). Consequently, a $0.38/acre subsidy for all fields would provide the economic incentive for farmers of these marginal fields to adopt VRT, while a $0.22/acre subsidy would exclude only Fields 2 and 7 from profitable adoption of VRT. The amount of subsidy adopted by policymakers would depend on the perceived tradeoffs between the environmental benefits in terms of the magnitudes of the NLDs and the cost of the subsidy. For example, the $0.38/acre subsidy for Field 2 (0-20-80) would reduce nitrogen loss by 2.10 lb/acre compared with the lower $0.20/acre subsidy for Field 7 (0-70-30) that would reduce nitrogen loss even more (2.91 lb/acre).

The impacts of the two nitrogen-restriction policies on $\tilde{\text{RVRT}}$, NAD, and NLD are presented in Tables 7, 8, and 9, respectively. Policy impacts were evaluated by comparing results to the no-restriction case, assuming Rainfall Scenario I was expected and realized. When nitrogen application was restricted to not more than 95 percent of the URT amount, the $\tilde{\text{RVRT}}$s became greater than C ($3.00/acre) for eight of the 11 marginal fields (Fields 7, 16, 25, 33, 40, 46, 51, and 55). All of these fields had 30 percent Loring soil. The $\tilde{\text{RVRT}}$s for Fields 2, 11, and 20 remained lower than $3.00/acre and actually decreased below those for the no-restriction case. The $\tilde{\text{RVRT}}$s for these fields decreased because on fields that contained from 50 to 90 percent Loring soil the nitrogen restriction caused yields to decline more for VRT than for URT. These differences in yield reductions between the two cases overshadowed the cost-reduction advantage VRT had relative to URT that was caused by the NADs changing from positive levels to zero (Table 8). When a field contained less than 50 percent Loring soil, the nitrogen restriction caused yields to decline less for VRT than for URT complementing the cost-reduction advantage of VRT over URT.

The reason for implementing a nitrogen-re-

Table 7. Return to Variable Rate Technology under Three Nitrogen Restriction Policies for 63 Hypothetical Corn Fields when Rainfall Scenario I was Expected and Realized

		$R\dot{V}RT$ or $R\tilde{V}RT$[a]					$R\dot{V}RT$ or $R\tilde{V}RT$		
Field Number	Soil Mix[b]	No N Rest.[c]	95% N Rest.[d]	N Loss Rest.[e]	Field Number	Soil Mix	No N Rest.	95% N Rest.	N Loss Rest.
			$/acre					$/acre	
1	0-10-90	**1.46**[f]	**1.38**	**1.57**	32	30-30-40	3.59	3.98	7.73
2	0-20-80	**2.62**	**2.48**	3.05	33	30-40-30	**2.86**	3.40	7.87
3	0-30-70	3.48	3.29	4.41	34	30-50-20	**1.94**	**2.48**	7.06
4	0-40-60	3.93	3.80	5.61	35	30-60-10	**0.95**	**1.31**	4.43
5	0-50-50	3.91	4.00	6.58	36	30-70-0	**0.00**	**0.00**	**0.00**
6	0-60-40	3.50	3.86	7.20	37	40-0-60	4.15	4.03	6.19
7	0-70-30	**2.80**	3.32	7.29	38	40-10-50	4.08	4.20	7.22
8	0-80-20	**1.91**	**2.43**	6.46	39	40-20-40	3.62	4.02	7.92
9	0-90-10	**0.93**	**1.29**	3.94	40	40-30-30	**2.88**	3.43	8.07
10	10-0-90	**1.55**	**1.47**	**1.67**	41	40-40-20	**1.95**	**2.50**	7.27
11	10-10-80	**2.70**	**2.56**	3.16	42	40-50-10	**0.95**	**1.32**	4.62
12	10-20-70	3.55	3.36	4.54	43	40-60-0	**0.00**	**0.00**	**0.00**
13	10-30-60	3.98	3.86	5.75	44	50-0-50	4.12	4.24	7.39
14	10-40-50	3.95	4.05	6.73	45	50-10-40	3.65	4.06	8.11
15	10-50-40	3.53	3.90	7.38	46	50-20-30	**2.90**	3.45	8.28
16	10-60-30	**2.82**	3.35	7.47	47	50-30-20	**1.96**	**2.51**	7.49
17	10-70-20	**1.92**	**2.45**	6.65	48	50-40-10	**0.96**	**1.33**	4.81
18	10-80-10	**0.94**	**1.30**	4.10	49	50-50-0	**0.00**	**0.00**	**0.00**
19	10-90-0	**0.00**	**0.00**	**0.00**	50	60-0-40	3.68	4.09	8.30
20	20-0-80	**2.78**	**2.64**	3.28	51	60-10-30	**2.92**	3.48	8.50
21	20-10-70	3.62	3.43	4.67	52	60-20-20	**1.97**	**2.53**	7.72
22	20-20-60	4.04	3.92	5.89	53	60-30-10	**0.96**	**1.34**	5.01
23	20-30-50	3.99	4.10	6.89	54	60-40-0	**0.00**	**0.00**	**0.00**
24	20-40-40	3.56	3.94	7.55	55	70-0-30	**2.93**	3.50	8.72
25	20-50-30	**2.84**	3.38	7.67	56	70-10-20	**1.98**	**2.54**	7.96
26	20-60-20	**1.93**	**2.47**	6.85	57	70-20-10	**0.96**	**1.34**	5.22
27	20-70-10	**0.94**	**1.31**	4.26	58	70-30-0	**0.00**	**0.00**	**0.00**
28	20-80-0	**0.00**	**0.00**	**0.00**	59	80-0-2	**1.99**	**2.56**	8.21
29	30-0-70	3.69	3.49	4.80	60	80-10-10	**0.97**	**1.35**	5.44
30	30-10-60	4.09	3.97	6.04	61	80-20-0	**0.00**	**0.00**	**0.00**
31	30-20-50	4.03	4.15	7.06	62	90-0-10	**0.97**	**1.35**	5.68
					63	90-10-0	**0.00**	**0.00**	**0.00**

[a] Abbreviations used include $R\dot{V}RT$ (optimal return to variable rate technology), $R\tilde{V}RT$ (return to variable rate technology under a nitrogen restriction), and N (nitrogen per acre).
[b] Percentages of the field in Collins, Memphis, and Loring soils, respectively.
[c] No fertilizer N restriction.
[d] Fertilizer nitrogen restricted to 95% of URT (Uniform Rate Technology) unrestricted alternative.
[e] URT fertilizer nitrogen restricted so nitrogen loss under URT is same as under VRT.
[f] RVRTs less than custom charges ($3.00/acre) are shown in bold.

striction policy would be to reduce nitrogen lost to the environment. Not only would this policy induce farmers to use VRT on more of their fields, reducing nitrogen loss on those fields by about three lb/acre, but the amount of nitrogen lost per acre from all VRT fields would be reduced slightly relative to URT amounts (Table 9). The largest reductions in nitrogen loss for the 95-percent nitrogen-restriction policy compared to the no-restriction case (0.18 to 0.19 lb/acre) would be on VRT fields with 70 percent Loring soil.

Table 8. Difference in Fertilizer Nitrogen Application under Three Nitrogen Restriction Policies for 63 Hypothetical Corn Fields when Rainfall Scenario I was Expected and Realized

		NAD[a]					NAD		
Field Number	Soil Mix[b]	No N Rest.[c]	95% N Rest.[d]	N Loss Rest.[e]	Field Number	Soil Mix	No N Rest.	95% N Rest.	N Loss Rest.
			lb/acre					lb/acre	
1	0-10-90	0.37	0.00	3.41	32	30-30-40	1.06	0.00	18.81
2	0-20-80	0.66	0.00	6.71	33	30-40-30	0.93	0.00	20.33
3	0-30-70	0.87	0.00	9.87	34	30-50-20	0.72	0.00	20.35
4	0-40-60	1.01	0.00	12.84	35	30-60-10	0.41	0.00	16.76
5	0-50-50	1.06	0.00	15.51	36	30-70-0	0.00	0.00	0.09
6	0-60-40	1.03	0.00	17.71	37	40-0-60	1.06	0.00	14.09
7	0-70-30	0.91	0.00	19.13	38	40-10-50	1.11	0.00	16.85
8	0-80-20	0.70	0.00	19.04	39	40-20-40	1.07	0.00	19.18
9	0-90-10	0.40	0.00	15.44	40	40-30-30	0.94	0.00	20.74
10	10-0-90	0.39	0.00	3.67	41	40-40-20	0.72	0.00	20.80
11	10-10-80	0.68	0.00	6.99	42	40-50-10	0.41	0.00	17.23
12	10-20-70	0.89	0.00	10.16	43	40-60-0	0.00	0.00	0.11
13	10-30-60	1.02	0.00	13.15	44	50-0-50	1.12	0.00	17.20
14	10-40-50	1.07	0.00	15.84	45	50-10-40	1.08	0.00	19.55
15	10-50-40	1.04	0.00	18.07	46	50-20-30	0.95	0.00	21.16
16	10-60-30	0.92	0.00	19.53	47	50-30-20	0.73	0.00	21.26
17	10-70-20	0.71	0.00	19.47	48	50-40-10	0.41	0.00	17.71
18	10-80-10	0.40	0.00	15.87	49	50-50-0	0.00	0.00	0.12
19	10-90-0	0.00	0.00	0.04	50	60-0-40	1.09	0.00	19.93
20	20-0-80	0.69	0.00	7.26	51	60-10-30	0.95	0.00	21.58
21	20-10-70	0.90	0.00	10.46	52	60-20-20	0.73	0.00	21.74
22	20-20-60	1.04	0.00	13.46	53	60-30-10	0.41	0.00	18.20
23	20-30-50	1.08	0.00	16.17	54	60-40-0	0.00	0.00	0.12
24	20-40-40	1.05	0.00	18.44	55	70-0-30	0.96	0.00	22.01
25	20-50-30	0.93	0.00	19.93	56	70-10-20	0.74	0.00	22.21
26	20-60-20	0.71	0.00	19.91	57	70-20-10	0.42	0.00	18.71
27	20-70-10	0.40	0.00	16.31	58	70-30-0	0.00	0.00	0.11
28	20-80-0	0.00	0.00	0.07	59	80-0-20	0.74	0.00	22.70
29	30-0-70	0.92	0.00	10.75	60	80-10-10	0.42	0.00	19.24
30	30-10-60	1.05	0.00	13.77	61	80-20-0	0.00	0.00	0.08
31	30-20-50	1.10	0.00	16.51	62	90-0-10	0.42	0.00	19.78
					63	90-10-0	0.00	0.00	0.05

[a] NAD is the amount of nitrogen applied with VRT minus the amount applied with URT (Uniform Rate Technology).
[b] Percentages of the field in Collins, Memphis, and Loring soils, respectively.
[c] No fertilizer nitrogen (N) restriction.
[d] Fertilizer nitrogen (N) restricted to 95% of URT unrestricted alternative.
[e] URT fertilizer nitrogen (N) restricted so that nitrogen loss under URT is the same as under VRT.

If the amount of nitrogen lost to the environment using URT is constrained to be the same as for VRT (NLDs in Table 9 equal 0 lb/acre), all but 11 of 63 fields would have $R\tilde{V}RT$ greater than C. These 11 fields contained either 0 or 90 percent Loring soil regardless of the proportions of the field in Collins or Memphis soils. They had too little spatial variability to allow VRT to be more profitable than URT even under this onerous nitrogen restriction. Farmers using either VRT or URT were not economically better off under this nitrogen restriction policy, but their losses were less using VRT than using URT

Table 9. Difference in Nitrogen Loss under Three Nitrogen Restriction Policies for 63 Hypothetical Corn Fields when Rainfall Scenario I was Expected and Realized

		NLD[a]					NLD		
Field Number	Soil Mix[b]	No N Rest.[c]	95% N Rest.[d]	N Loss Rest.[e]	Field Number	Soil Mix	No N Rest.	95% N Rest.	N Loss Rest.
			lb/acre					lb/acre	
1	0-10-90	−1.17	−1.28	0.00	32	30-30-40	−3.42	−3.52	0.00
2	0-20-80	−2.10	−2.27	0.00	33	30-40-30	−3.01	−3.06	0.00
3	0-30-70	−2.79	−2.97	0.00	34	30-50-20	−2.31	−2.33	0.00
4	0-40-60	−3.22	−3.39	0.00	35	30-60-10	−1.31	−1.31	0.00
5	0-50-50	−3.39	−3.53	0.00	36	30-70-0	0.00	0.00	0.00
6	0-60-40	−3.29	−3.39	0.00	37	40-0-60	−3.47	−3.64	0.00
7	0-70-30	−2.91	−2.97	0.00	38	40-10-50	−3.60	−3.74	0.00
8	0-80-20	−2.24	−2.26	0.00	39	40-20-40	−3.46	−3.56	0.00
9	0-90-10	−1.28	−1.27	0.00	40	40-30-30	−3.04	−3.09	0.00
10	10-0-90	−1.26	−1.37	0.00	41	40-40-20	−2.33	−2.35	0.00
11	10-10-80	−2.18	−2.35	0.00	42	40-50-10	−1.32	−1.32	0.00
12	10-20-70	−2.86	−3.04	0.00	43	40-60-0	0.00	0.00	0.00
13	10-30-60	−3.28	−3.46	0.00	44	50-0-50	−3.65	−3.79	0.00
14	10-40-50	−3.44	−3.59	0.00	45	50-10-40	−3.50	−3.60	0.00
15	10-50-40	−3.34	−3.43	0.00	46	50-20-30	−3.08	−3.13	0.00
16	10-60-30	−2.95	−3.00	0.00	47	50-30-20	−2.36	−2.37	0.00
17	10-70-20	−2.27	−2.28	0.00	48	50-40-10	−1.34	−1.33	0.00
18	10-80-10	−1.29	−1.29	0.00	49	50-50-0	0.00	0.00	0.00
19	10-90-0	0.00	0.00	0.00	50	60-0-40	−3.55	−3.64	0.00
20	20-0-80	−2.26	−2.43	0.00	51	60-10-30	−3.11	−3.16	0.00
21	20-10-70	−2.93	−3.12	0.00	52	60-20-20	−2.38	−2.39	0.00
22	20-20-60	−3.35	−3.52	0.00	53	60-30-10	−1.35	−1.34	0.00
23	20-30-50	−3.50	−3.64	0.00	54	60-40-0	0.00	0.00	0.00
24	20-40-40	−3.38	−3.48	0.00	55	70-0-30	−3.14	−3.19	0.00
25	20-50-30	−2.98	−3.03	0.00	56	70-10-20	−2.40	−2.41	0.00
26	20-60-20	−2.29	−2.31	0.00	57	70-20-10	−1.36	−1.35	0.00
27	20-70-10	−1.30	−1.30	0.00	58	70-30-0	0.00	0.00	0.00
28	20-80-0	0.00	0.00	0.00	59	80-0-20	−2.42	−2.43	0.00
29	30-0-70	−3.00	−3.19	0.00	60	80-10-10	−1.37	−1.36	0.00
30	30-10-60	−3.41	−3.58	0.00	61	80-20-0	0.00	0.00	0.00
31	30-20-50	−3.55	−3.69	0.00	62	90-0-10	−1.38	−1.37	0.00
					63	90-10-0	0.00	0.00	0.00

[a] NLD is the amount of nitrogen (N) lost to the environment with VRT minus the amount lost with URT (Uniform Rate Technology).
[b] Percentages of the field in Collins, Memphis, and Loring soils, respectively.
[c] No fertilizer nitrogen restriction.
[d] Fertilizer nitrogen restricted to 95% of URT unrestricted alternative.
[e] URT fertilizer nitrogen restricted so that nitrogen loss under URT is the same as under VRT.

(Table 7), except on fields that were extremely uniform in yield response potential.

Conclusions

This study investigated the economic and environmental effects of using variable rate technology (VRT) for nitrogen application on corn fields. Corn yield and nitrogen loss response functions were estimated for three weather scenarios and three soil types from data generated by the Environmental Policy Integrated Climate (EPIC) simulator. These meta-response functions were used to analyze the economic and environmental impacts of 1) field spatial variability among management zones with different yield responses, 2) correct versus incorrect weather expectations, and 3) environmental policy options for inducing farmers to adopt VRT.

This analysis evaluated VRT versus URT for only one crop produced in fields with a limited number of soil types. Actual fields in many geographic areas, such as West Tennessee, can contain a wide variety of soil types suited to producing several major crops in rotation or otherwise. Proper economic and environmental evaluation of VRT versus URT requires reliable estimates of yield response and nitrogen loss functions for these soil types and crops. Over the years a limited number of field experiments have allowed estimation of a patchwork of yield response functions for some geographic areas, but usually these experiments have not included environmental data nor sufficient years to effectively evaluate the effects of weather on yield response. The demand for VRT will likely increase substantially in the future, requiring estimates of yield response functions for a growing number of farmers. A concerted effort to estimate and document yield and environmental response for a variety of crops, soil series, and weather conditions would be beneficial to policymakers, agribusiness firms, and farmers who are contemplating the adoption of VRT. Until such data become available, simulated data could be used to model these yield and environmental response functions. These meta-response functions and the economic model developed in this article could be made available to policymakers, agribusiness firms, and farmers in a user-friendly spreadsheet model that would allow them to evaluate the economic and environmental effects of adopting VRT on a specific field.

Results suggest that VRT may reduce nitrogen loss compared with URT. This conclusion depends on the soil types within a field and the amount of spatial variability. Results also suggest that economic incentives from subsidies and nitrogen-restriction policies could induce URT farmers to reduce nitrogen loss by switching to VRT on some fields. The amount of incentive required for a producer to adopt VRT depends on the spatial variability within the farmer's fields. Some fields have sufficient spatial variability for VRT to be profitable without additional economic incentives, while on less spatially variable fields additional economic incentives would be required for VRT use. The question of concern for policymakers is whether the damage caused to the environment through less efficient input use with URT is greater than the cost of policies encouraging the use of VRT. Results have shown that VRT can reduce nitrogen loss compared to URT and that subsidy and nitrogen-restriction policies can provide economic incentive for farmers to switch to VRT on some fields. Further research is required to determine if the environmental benefits of VRT outweigh the cost of implementing various policy options.

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