Economic and Environmental Benefits of Variable Rate Application of Nitrogen to Corn Fields: Role of Variability and Weather

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Abstract

The use of meta-response functions based on EPIC-generated data resulted in comparisons between variable (VRAT) and uniform rate application technologies for 36 simulated fields. VRAT was more profitable and less nitrogen was lost to the environment in most cases. When spatial variability was small, uniform rate application techniques were adopted. However, when nitrogen use is restricted, VRAT is used on all simulated fields.

Key Words
Precision farming, site-specific farming, spatial variability, nitrogen restriction, rainfall, EPIC, crop growth simulation model

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Several studies have assessed the economic potential of variable rate application technology (VRAT) (Carr et al., 1991; English et al., 1998; Fiez et al., 1994; Forcella, 1993; Hayes et al., 1994; Hibbard et al., 1993; Snyder, 1996; Wibawa et al., 1993). However, most earlier studies ignored the effects of variable rate input application on the environment (Watkins et al., 1998; Lowenberg-DeBoer, 1996; Swinton and Ahmed, 1996).

Precision farming addresses site-specific crop needs. Its component technologies enable the farmers to understand the changing plant growth environment across the field, estimate the nutrient requirements of 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/reduced input use, while reducing the environmental harms associated with the excessive use of agricultural chemicals (Kitchen et al.; Koo and Williams; National Research Council; Sawyer; Watkins et al.).

A profit maximizing farmer is guided primarily by the expected economic benefits from the VRAT adoption decision. The economic benefits of VRAT are determined by spatial variability and the magnitude of spatial yield differences (English et al.). The specific objectives of this study were (i) to examine the economic feasibility of variable rate nutrient application vis-à-vis changing spatial variability and weather conditions, and (ii) to test the hypothesis that precision farming provides environmental benefits.

Methods

Using the Environmental Policy Integrated Climate (EPIC) crop growth simulation model for corn to develop information on weather and nitrogen-crop responses for three different West Tennessee soils under three different rainfall scenarios, nine quadratic plus plateau metamodels (y=f(n)) were estimated (equations 1 and 2); one for each soil type and rainfall scenario

$$Y = \alpha + \beta N + \gamma N^2 \qquad \text{if } N < N^c \qquad [1]$$

$Y = Y^p$ if N ƒ N^c [2]

Where Y = corn yield (bu/acre); N = nitrogen application rate (lb/acre); α, β and γ are intercept, linear coefficient and quadratic coefficient respectively obtained by fitting the model to the data; and the N^c and Y^p are the critical N rate and plateau yield, also obtained by fitting the model. The NLIN procedure (SAS Institute) was used to estimate the model. Field average response functions were estimated from the data based on land mix and rainfall scenario. These average response functions were used to determine the rate of application under uniform rate application technology (URAT).

Thirty-six different 100-acre fields were simulated, each having a different land mix (Table 1). The response functions determined the optimal level of nitrogen application for a given soil and a given weather pattern. This information was used to simulate production, assuming expected and actual weather were the same. The net return differential between VRAT and URAT (return to VRAT) was estimated for each soil in the field and summed over the entire field. If the return to VRAT exceeded the additional cost of VRAT ($300), the adoption of VRAT would be economically beneficial compared to URAT.

Using the monthly rainfall data recorded by the Covington weather station in West Tennessee (U. S. Department of Commerce), three rainfall scenarios were created and used in EPIC. Scenario 1 was created with average rainfall for each month over the period 1988-1997. Scenarios 2 and 3 were created by decreasing the monthly average rainfall by 0.5 standard deviation and 1 standard deviation, respectively. EPIC was forced to generate adjusted weather to the mean monthly minimum and maximum temperatures were the same as reported at the Covington weather station. Rainfall was the same for each year of simulation.

Custom hiring the necessary VRAT services is the typical means of using this relatively new technology (English et al.). The additional custom charge incurred when switching from URAT to VRAT of N was $3/acre[1]. A corn price (P_C) of $2.79/bu and a urea price (P_n) of $0.26/lb of N was used in the analysis[2] (Tennessee Department of Agriculture).

Analysis of the first objective was conducted in three steps. First, the producer was assumed to select the appropriate response function that matched expected weather. Second, a response function representing the expected weather scenario was used to determine optimal input application rates. Finally, returns to VRAT were evaluated with respect to spatial variability as represented by the land mix in each of the 36 fields.

The second objective weighed the economic and environmental consequences of a restriction in the amount of nitrogen applied on the fields identified as not economically benefiting from VRAT under the unconstrained, scenario 3 rainfall case. A comparison was conducted evaluating net returns between VRAT and URAT when nitrogen availability was constrained.

Economic Analysis of Precision Farming

Total optimal returns above N costs from the field with VRAT (R^{*}_{VRT}) can be estimated as

$$R^{*}_{VRT} = \sum A_i(P_c Y_i^{*} - P_n N_i^{*}) \qquad [3]$$

Where A_i is total area in soil i, P_c is the price of the crop, P_n is the price of nitrogen, N_i^{*} is the optimal nitrogen applied on soil i and Y_i^{*} is the yield on soil i. Similarly, the optimum returns above N costs from the field under URT (R^{*}_{URT}) can be expressed as:

$$R^{*}_{URT} = P_c Y^{*}_{FLD} - P_n N^{*}_{FLD} \qquad [4]$$

where Y_{FLD} and N_{FLD} are the optimum average yield and nitrogen level applied assuming an average field response function weigted by A_i.

The return to VRAT is $R^{*}_{VRT} - R^{*}_{URT} = R\dot{V}RT$. With C as the additional custom charges for VRAT the necessary economic condition for VRAT adoption on this field is $R\dot{V}RT$ ƒ C. If $R\dot{V}RT$ is greater than C, the farmer was assumed to adopt VRAT and expect economic gains. $R\dot{V}RT$ was calculated for each of the 36 fields to determine how many of them would switch to VRAT subsequent to the realization of a particular weather scenario.

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[1] This \$3 cost for VRAT was obtained through personal communication with two local farmer's cooperatives in West Tennessee. (Names of providers are not given to prevent disclosure.)

[2] Prices used in this analysis were mean annual averages reported over the 1993 to 1997 period.

Environmental Analysis of Precision Farming

The study analyzed the environmental consequences of N application under both URAT and VRAT. Following Chowdhury and Lacewell and Wu et al., environmental data generated with EPIC were synthesized into functional relationships. The total amount of N lost (N_{loss}) was calculated by adding pounds of N lost in leaching, surface runoff and sub surface flow obtained from EPIC output (V.W. Benson, personal communication) for each soil series under each rainfall scenario. Preliminary analysis suggested that N_{loss} was linear in N applied (Wu et al) and ordinary least squares (SAS Institute) was used to estimate these relationships. The estimated equations were used to predict N_{loss} as a consequence of the profit-maximizing behavior of farmers under both N application methods. Further, the N Loss Difference (NLD), defined as N_{loss} with VRAT minus N_{loss} with URAT, and the N Applied Difference (NAD), defined as the amount of N applied using VRAT less the amount of N applied using URAT, were calculated for each field under each rainfall scenario.

Restricting N Application

When N application is restricted, VRAT applies each unit of the scarce input based on its marginal value whereas, the URAT places the input on the field uniformly not accounting for differences in marginal physical product between soils within the field. This should increase the return to VRAT relative to URAT when compared to the unconstrained case. As a result, on those fields that do not switch to VRAT in the unconstrained case could switch under the constrained situation results. This study analyzed a restriction on the amount of N applied by constraining the URAT farmers to applying 95 percent of their URAT rate. A new net return above N cost ($\tilde{R}_{URT}$) for

URAT was determined by replacing the optimal N in the average response function with $0.95\ \mathrm{N}^{*}_{\mathrm{FLD}}$.

To determine nitrogen levels for VRAT under the constrained N situation, several steps were required. First, the amount of N allowed under the URAT constrained situation ($95\,\mathrm{N}^{*}_{\mathrm{FLD}}$) is compared to the VRAT unconstrained levels. If VRAT unconstrained levels used less then the URAT constrained situation, the optimal values for VRAT were used. If these rates required more fertilizer than the optimal VRAT then $\mathrm{N}_{\mathrm{i}}^{*}$ was reduced by equating the marginal physical products of the each soil given a reduction in the optimum uniform N rate from $\mathrm{N}^{*}_{\mathrm{FLD}}$ to $.95\ \mathrm{N}^{*}_{\mathrm{FLD}}$. These VRAT rates were then compared to the economic optimum unconstrained values and the lesser of the two levels were used for VRAT. Once the optimal level of fertilizer for each soil was determined, yield and $\tilde{\mathrm{R}}_{\mathrm{VRT}}$ were estimated. Referring to the difference $\tilde{\mathrm{R}}_{\mathrm{VRT}} - \tilde{\mathrm{R}}_{\mathrm{URT}}$ as the constrained return to variable rate technology ($\mathrm{R}\tilde{\mathrm{V}}\mathrm{RT}$), the necessary condition for VRAT adoption because $\mathrm{R}\tilde{\mathrm{V}}\mathrm{RT}\ f\ \mathrm{C}$. Farmers who found URAT more beneficial in the unconstrained case could switch to VRAT under the N restriction situation.

Results

Table 2 presents the estimated corn yield response functions for Collins, Memphis and Loring series under rainfall scenarios 1, 2, and 3. The linear and quadratic coefficients for all equations had the expected positive and negative signs respectively and almost all were significantly different from zero. Almost all coefficients for the average response functions were significant and all had the expected signs (not reported here). The estimated $\mathrm{N}_{\mathrm{loss}}$ response functions had significant coefficients for applied N, with expected positive signs (Mahajanashetti).

The results revealed that a farming decision supported by correct weather expectations was important in determining the economic gains from VRAT adoption. Most of the 36 fields benefited economically from VRAT adoption (Table 3). More fields used VRAT when rainfall was less than average. Under average rainfall, fields 8,15, 21, 26, 30, 33, 35, and 36 would be farmed with URAT. However, if one standard deviation less rainfall were expected, fields 21, 26, and 30 would switch to VRAT. The results also showed considerable environmental benefits in terms of reduced N loss from leaching, subsurface flow and surface runoff. Spatial variability influenced the magnitude of $R\dot{V}RT$ and the extent to which N_{loss} was reduced. Field variability is important as demonstrated by fields with low amounts of Loring soils (10 percent) (fields 8, 15, 33, 35, and 36). Farmers of these fields would not adopt VRAT under any of the rainfall scenarios because yield response variability was low.

The impacts of restricting N are presented for fields 8, 15, 33, 35, and 36 (Table 4). When farmers were constrained to apply not more than 95 percent of the N applied with URAT, return was greater in the VRAT option than when URAT was used. In all five cases VRAT was more attractive then URAT. Adoption of VRAT would reduce N_{loss} considerably on all fields. For example, on field 8, total N_{loss} would decrease from 1073 pounds to 492 pounds, and on field 36, N_{loss} would decrease from around 1039 lb to 534 lb.

Optimized corn output falls for URAT as conditions change form unconstrained to constrained N use. However, on all five fields, production actually increased when the restricted quantity of N was precisely applied with VRAT. For example, field 8 would produce 102 bushels less corn when N amount was restricted and was applied uniformly, compared to the unconstrained situation when N was applied uniformly. Conversely, the variable rate application of the restricted quantity of N increased production by more than 20 bushels when compared to the unrestricted application using URAT in the unconstrained case.

Under the N constrained case, returns above N costs fall for both VRAT ($\tilde{R}_{vrt}$) and URAT ($\tilde{R}_{vrt}$)compared to the unconstrained optimum (R^{*}_{URT}); but the decline is less with the VRAT because of the projected increase in output. For field 8, restricting N application meant a decrease in returns above N costs of $86.75 assuming the farmer had to continue to use URAT; however, with VRAT available, precision application of the restricted amount of N would be economically more attractive with returns above N cost falling by $23.40.

Conclusions

This simulation study investigated economic and environmental effects of custom hired VRAT adoption. For analyzing the impacts of spatial variability on the outcomes of technology adoption, a total of 36 hypothetical fields were created with varying proportions of three soil series suited to growing corn. Further, to investigate the effects of weather on the economic benefits from the technology, different rainfall scenarios were created. The Environmental Policy Integrated Climate (EPIC) simulator was used to estimate corn yield and N loss response functions for applied N.

Most of the study fields benefited economically from VRAT. The extent of benefits varied across fields depending upon spatial variability and amount of rainfall received. The results also showed considerable environmental benefits in terms of reduced N loss from leaching, subsurface flow and surface runoff.

The study analyzed the impacts of restricting N application for motivating URAT farmers to switch to VRAT and help reduce environmental degradation. When N application was restricted, the return to VRAT went up and exceeded custom charges inducing farmers to adopt VRAT.

Table 1. Proportions of Collins, Memphis and Loring Soils 1n the Hypothetical Fields

Field No.	Land Proportions in the Field			Field No.	Land Proportions in the Field		
	Collins	Memphis	Loring		Collins	Memphis	Loring
1	10	10	80	19	30	40	30
2	10	20	70	20	30	50	20
3	10	30	60	21	30	60	10
4	10	40	50	22	40	10	50
5	10	50	40	23	40	20	40
6	10	60	30	24	40	30	30
7	10	70	20	25	40	40	20
8	10	80	10	26	40	50	10
9	20	10	70	27	50	10	40
10	20	20	60	28	50	20	30
11	20	30	50	29	50	30	20
12	20	40	40	30	50	40	10
13	20	50	30	31	60	10	30
14	20	60	20	32	60	20	20
15	20	70	10	33	60	30	10
16	30	10	60	34	70	10	20
17	30	20	50	35	70	20	10
18	30	30	40	36	80	10	10

Table 2. Estimated Corn Yield Response Functions for Applied N for Collins, Memphis and Loring Soils under Three Rainfall Scenarios

Soil/Scenario	Equation	R^2
<u>Collins:</u>		
Rainfall Scenario 1	$Y = 19.401 + 1.664N - 0.00391N^2$ if $N < 212.57$	0.999
	(5.049)[*] (0.108) (0.000458)	
	$Y = 196.22$ if $N \mu 212.57$	
Rainfall Scenario 2	$Y = 18.727 + 1.695N - 0.0039N^2$ if $N < 217.47$	0.994
	(5.533) (0.116) (0.000481)	
	$Y = 203.05$ if $N \mu 217.47$	
Rainfall Scenario 3	$Y = 22.366 + 1.6N - 0.00542N^2$ if $N < 147.53$	0.996
	(2.871) (0.0889) (0.000533)	
	$Y = 140.36$ if $N \mu 147.53$	
<u>Memphis:</u>		
Rainfall Scenario 1	$Y = 19.401 + 1.664N - 0.00391N^2$ if $N < 212.57$	0.999
	(5.049) (0.108) (0.000458)	
	$Y = 196.22$ if $N \mu 212.57$	
Rainfall Scenario 2	$Y = 18.727 + 1.695N - 0.0039N^2$ if $N < 217.47$	0.994
	(5.533) (0.116) (0.000481)	
	$Y = 203.05$ if $N \mu 217.47$	
Rainfall Scenario 3	$Y = 22.094 + 1.677N - 0.00509N^2$ if $N < 164.76$	0.994
	(4.401) (0.122) (0.000653)	
	$Y = 160.24$ if $N \mu 164.76$	
<u>Loring:</u>		
Rainfall Scenario 1	$Y = 5.674 + 1.639N - 0.00632N^2$ if $N < 129.61$	0.841
	(19.130) (0.689) (0.00472)	
	$Y = 111.90$ if $N \mu 129.61$	
Rainfall Scenario 2	$Y = 9.398 + 1.368N - 0.00621N^2$ if $N < 110.18$	0.985
	(3.883) (0.165) (0.00133)	
	$Y = 84.76$ if $N \mu 110.18$	
Rainfall Scenario 3	$Y = 10.72 + 0.491N - 0.00361N^2$ if $N < 67.88$	0.999
	(0.00408) (0.000299) (0.000004)	
	$Y = 27.37$ if $N \mu 67.88$	

[*] Numbers in parentheses are asymptotic standard errors. Intercepts and linear and quadratic coefficients were all significant at the $\alpha = 0.10$ level for Collins and Memphis series under all the three scenarios, and for Loring series under scenario 2 and 3. In the equation for Loring series under scenario 1, only linear coefficient was found significant at the $\alpha = 0.10$ level.

Table 3. Optimum return to VRAT ($R\dot{V}RT$), N application difference (NAD) and N loss difference (NLD) for 36 hypothetical corn fields under two rainfall scenarios

Field Number	Rainfall Scenario 1			Rainfall Scenario 3		
	$R\dot{V}RT$[¶]	NAD[#]	NLD[†]	$R\dot{V}RT$[¶]	NAD[#]	NLD[†]
	Dollars	Pounds	Pounds	Dollars	Pounds	Pounds
1	1141.20	276.80	-384.92	1444.17	-3418.05	-2520.54
2	1406.15	249.08	-549.80	1470.06	-3899.59	-2829.64
3	1467.22	218.45	-654.52	1353.57	-3802.31	-2751.80
4	1442.44	411.69	-645.88	1173.55	-3468.96	-2494.71
5	1269.63	490.73	-615.20	965.74	-2950.17	-2112.49
6	973.85	460.14	-548.91	743.17	-2315.19	-1651.05
7	623.32	382.73	-427.13	512.54	-1592.06	-1134.51
8	**273.45**[††]	245.65	-245.64	**276.60**	-811.78	-580.70
9	1406.15	249.08	-558.60	1372.50	-3571.67	-2621.77
10	1467.22	218.45	-662.07	1295.60	-3626.71	-2628.93
11	1442.44	411.69	-652.52	1144.64	-3328.59	-2402.75
12	1269.63	490.73	-620.76	956.04	-2845.67	-2047.47
13	973.85	460.14	-553.22	747.51	-2232.78	-1606.11
14	623.32	382.73	-430.12	526.44	-1551.57	-1109.72
15	**273.45**	245.65	-247.22	**298.21**	-829.02	-572.35
16	1467.22	218.45	-669.62	1224.41	-3389.73	-2483.42
17	1442.44	411.69	-659.16	1102.00	-3172.58	-2305.91
18	1269.63	490.73	-626.32	933.72	-2736.73	-1981.31
19	973.85	460.14	-557.54	738.62	-2190.72	-1568.92
20	623.32	382.73	-433.11	529.70	-1525.29	-1086.82
21	**273.45**	245.65	-248.80	310.92	-805.79	-560.93
22	1442.44	411.69	-665.80	1044.96	-3019.45	-2209.93
23	1269.63	490.73	-631.88	897.70	-2648.73	-1920.38
24	973.85	460.14	-561.85	718.98	-2141.79	-1530.38
25	623.32	382.73	-436.10	522.92	-1501.62	-1064.25
26	**273.45**	245.65	-250.38	314.45	-795.33	-550.46
27	1269.63	490.73	-637.43	850.46	-2545.48	-1855.59
28	973.85	460.14	-566.16	689.66	-2063.38	-1486.14
29	623.32	382.73	-439.09	506.76	-1459.87	-1039.24
30	**273.45**	245.65	-251.96	309.03	-787.05	-540.13
31	973.85	460.14	-570.47	650.57	-1970.32	-1439.05
32	623.32	382.73	-442.08	481.47	-1401.91	-1012.02
33	**273.45**	245.65	-253.53	**294.88**	-761.76	-528.50
34	623.32	382.73	-445.07	446.46	-1359.82	-986.92
35	**273.45**	245.65	-255.11	**272.10**	-749.75	-517.85
36	**273.45**	245.65	-256.69	**241.10**	-712.46	-505.27

[¶] Optimum returns above N costs from the field under VRAT minus optimum returns under URAT, with unconstrained N availability.

[#] Total N application under VRAT minus total N application under URAT.

[†] Total N loss by leaching, surface runoff and subsurface flow from the field under VRAT minus total N loss under URAT.

[††] $RVRT^{*}$'s that are less than the custom charges ($300) are shown in bold numbers; they indicate the cases in which VRAT adoption would not be economically feasible.

Table 4. Effects of N-restriction on production, returns and N-loss in five simulated fields managed with URAT in the unconstrained case when rainfall scenario 3 is expected

Field No.	Constraint on N Application	Production	Optimum Returns	N Loss	NLD
		(bu)	($)	(lb)	(lb)
8	No N constraints	14428.92	36304.88	1072.50	-580.70
	N-constrained with VRAT	14452.41	36281.48	491.81	-523.26
	N-constrained no VRAT option	14326.98	36218.13	1015.10	NA
	Effects on output and returns				
	With VRAT Option	**+ 23.49**	**– 23.40**	NA	NA
	Without VRAT option	**– 101.94**	**– 86.75**	NA	NA
15	No N constraints	14225.27	35775.32	1070.19	-572.35
	N-constrained with VRAT	14254.90	35773.53	497.83	-515.44
	N-constrained no VRAT option	14127.37	35697.88	1013.28	NA
	Effects on output and returns				
	With VRAT Option	**+ 29.63**	**– 1.79**	NA	NA
	Without VRAT option	**– 97.90**	**– 77.44**	NA	NA
33	No N constraints	13430.16	33746.84	1050.44	-528.50
	N-constrained with VRAT	13464.86	33741.71	521.94	-474.19
	N-constrained no VRAT option	13338.03	33676.07	996.13	NA
	Effects on output and returns				
	With VRAT Option	**+ 34.70**	**– 5.13**	NA	NA
	Without VRAT option	**– 92.13**	**– 70.77**	NA	NA
35	No N constraints				
	N-constrained with VRAT	13267.35	33233.76	527.97	-464.25
	N-constrained no VRAT option	13149.02	33192.40	992.22	NA
	Effects on output and returns				
	With VRAT Option	**+ 27.66**	**– 27.89**	NA	NA
	Without VRAT option	**– 90.67**	**– 69.25**	NA	NA
36	No constraints	13049.82	32784.70	1039.27	-505.27
	N-constrained with VRAT option	13069.84	32725.80	534.00	-452.40
	N-constrained no VRAT option	12958.77	32711.80	986.39	NA
	Effects on output and returns				
	With VRAT Option	**+ 20.02**	**– 58.90**	NA	NA
	Without VRAT option	**– 91.05**	**– 72.90**	NA	NA

References

Benson, V.W. “EPIC: A Planning Tool for Soil and Water Conservation Programs.” In J.K. Clema (Ed.) *Proceedings of the 1989 Summer Computer Simulation Conference*. Conference Held at Austin, TX, July 24 – 27, 1989. San Diego, CA: The Society for Computer Simulation, 1989: 728 – 720.

Benson, V.W. Agricultural Economist, NRCS, Temple, TX. Personal Communication, October 1998.

Carr, P.M., G.R. Carlson, J.S. Jacobson, G.A. Nielsen, and E.O. Skogley. “Farming Soils, Not Fields: A Strategy for Increasing Fertilizer Profitability.” *Journal of Production Agriculture*, 4 (1), January-March 1991: 57 – 61.

Chowdhury, M.E., and R.D. Lacewell. “ Application of Sample Selection Model in Estimating Response Functions for Nitrate Percolation.” *Journal of Environmental management*, 48, 1996: 375 – 386.

English, B.C., R.K. Roberts, and S.B. Mahajanashetti. “Spatial Break-Even Variability for Variable Rate Technology Adoption.” Paper Presented at the Fourth International Conference on Precision Agriculture Held at St. Paul, MN, July 19-22, 1998.

Fiez, T.E., B.C. Miller, and W.L. Pan. “ Assessment of Spatially Variable Nitrogen Fertilizer Management in Winter Wheat.” *Journal of Production Agriculture*, 7 (1), January-March 1994: 86 – 93.

Forcella, Frank. “ Value of Managing Within-Field Variability.” In P.C. Robert, R.H. Rust, and W.E. Larson (Eds.) *Proceedings of Soil Specific Crop Management: A workshop on Research and Development Issues*. Workshop Held at Minneapolis, MN, April 14-16, 1992. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, 1993: 125 – 132.

Hayes, J.C., A. Overton, and J.W. Price. 1994. “Feasibility of Site-Specific Nutrient and Pesticide Applications.” In K.L. Campbell, W.D. Graham, and A. B. Bottcher (Eds.) *Proceedings of the Second Conference on Environmentally Sound Agriculture*. Conference Held at Orlando, FL, April 20-22, 1994. St. Joseph, MI: American Society of Agricultural Engineers, 1994: 62 – 68.

Hibbard, J.D., D.C. White, C.A. Hertz, R.H. Hornbaker, and B.J. Sherrick. “Preliminary Economic Assessment of Variable Rate Technology for Applying P and K in Corn Production.” Paper Presented at the Western Agricultural Economics Association Meeting, Edmonton, Alberta, July 1993.

Kitchen, N.R., K.A. Sudduth, S.J. Birrell, and S.C. Borgelt. “ Missouri Precision Agriculture Research and Education.” In P.C. Robert, R.H. Rust, and W.E. Larson (Eds.) *Proceedings of the Third International Conference on Precision Agriculture*. Conference

Held at Minneapolis, MN, June 23-26, 1996. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, 1996: 1091 – 1099.

Koo, S., and J.R. Williams. "Soil-Specific Production Strategies and Agricultural Contamination Levels in Northeast Kansas." In P.C. Robert, R.H. Rust, and W.E. Larson (Eds.) *Proceedings of the Third International Conference on Precision Agriculture*. Conference Held at Minneapolis, MN, June 23-26, 1996. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, 1996: 1079 – 1089.

Lowenberg-DeBoer, J. "Precision Farming and the new Information Technology: Implications for Farm Management, Policy, and Research: Discussion." *American Journal of Agricultural Economics*, 78 (December 1996):1281 – 1284.

Mahajanashetti, Shivakumar B., Precision Farming: An Economic and Environmental Analysis of Within -Field Variability, University of Tennessee-Knoxville, dissertation, May 1999.

National Research Council. *Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Production*. National Academy Press, Washington, D.C. 1997.

SAS Institute. SAS User's Guide: Statistics. 1985 ed. SAS Inst., Cary, NC.

Sawyer, J.E. "Concepts of Variable Rate Technology with Considerations for Fertilizer Application." *Journal of Production Agriculture*, 7 (2), April-June 1994:195 – 201.

Snyder C.J. " An Economic Analysis of Variable-Rate Nitrogen Management Using Precision Farming Methods." PhD Dissertation, Kansas State University, 1996.

Swinton, S.M., and Ahmad, Mubariq. "Returns to Farmer Investments in Precision Agriculture Equipment and Services." In P.C. Robert, R.H. Rust, and W.E. Larson (Eds.) *Proceedings of the Third International Conference on Precision Agriculture*. Conference Held at Minneapolis, MN, June 23-26, 1996. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, 1996: 1009 – 1018.

Tennessee Department of Agriculture. *Tennessee Agriculture*. Tennessee Agricultural Statistics Service, Nashville, TN. Several issues.

U.S. Department of Commerce. *Climatological Data, Tennessee*. National Oceanic and Atmospheric Administration (NOAA), National Climatic Data Center, Nashville, TN. Several issues.

Watkins, K.B., Y.C. Lu, and W.Y. Huang. “Economic Returns and Environmental Impacts of Variable Nitrogen Fertilizer and Water Applications.” Paper Presented at the Fourth International Conference on Precision Agriculture Held at St. Paul, MN, July 19-22, 1998.

Wibawa, W.D., D.L. Dludlu, L.J. Swenson, D.G. Hopkins, and W.C. Dhanke. “Variable Fertilizer Application Based on Yield Goal, Soil Fertility and Soil Map Unit.” *Journal of Production Agriculture*, 6 (2), April-June 1993: 255 – 261.

Wu, J., P.G. Laxminarayan, and B.A. Babcock. *Impacts of Agricultural Practices and Policies on Potential Nitrate Water Pollution in the Midwest and Northern Plains of the United States*. Center for Agricultural and Rural Development, Iowa State University. Working Paper 96-WP 148, February 1996.