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Economic and Environmental Evaluation of Variable Rate Nitrogen and Lime Application for Claypan Soil Fields

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Abstract. Variable Rate Technology (VRT) has the potential to increase crop yields and improve water quality relative to Uniform Rate Technology (URT). The effects on profitability and water quality of adopting VRT for nitrogen (N) and lime were evaluated for corn production on four claypan soil fields in north central Missouri under average to better than average weather conditions. Variable N and lime rates were based on measured topsoil depth and soil pH, respectively. VRT rates were compared to two different uniform N applications (URT-Nl based on the topsoil depth within these claypan soil fields, and URT-N2 based on a typical N rate for corn production in this area). Expected corn yield was predicted based on topsoil depth, soil pH, N rate, and lime rate. Water quality benefits of VRT relative to URT were evaluated based on potential leachable N. Sensitivity analyses were performed using simulated topsoil data for topsoil depth and soil pH. Results showed that VRT was more profitable than URT in the four sample fields under URT-N1, and in two of the four fields under URT-N2. Greater variation in topsoil depth and soil pH resulted in higher profitability and greater water quality benefits with VRT. Results support adoption of VRT for N and lime application for other claypan soil fields with characteristics similar to those in the fields used in this study.

Keywords: variable rate technology, claypan soils, profitability, water quality

Introduction

Variable rate fertilizer application based on within-field variability in soil properties has the potential to reduce under- and over-application of fertilizers, and thereby improve fertilizer use efficiency, crop yields and net farm returns (Fiez et al., 1994). Improved fertilizer use efficiency could reduce adverse environmental impacts of crop production, such as nitrogen (N) and phosphorus (P) contamination of surface and ground water. Profitability of variable rate technology (VRT) for application of N fertilizer is important to crop producers, natural resource conservation agencies, and policy makers who wish to reduce adverse environmental impacts of crop production. Studies of economic and environmental impacts of variable N application in crop production have been mixed. Some studies found VRT application of N to be superior to a uniform rate in terms of economic and water quality benefits (English et al., 1999; Thrikawala et al., 1999; Babcock and Pautsch, 1998; Schnitkey et al., 1996). In other studies, the economic and water quality benefits of VRT were not significant (Watkins et al., 1998; Qiu and Prato, 1999).

Better information about the economic and environmental impacts of VRT facilitates adoption of precision agricultural technologies. New technologies and implementation procedures that potentially impact the benefits and costs of VRT warrant evaluation. Such evaluation should be part of an iterative, continuous cycle of research, development, and deployment designed to improve site-specific technologies (National Research Council, 1997).

This study evaluated the economic and environmental impacts of variable rate N and lime applications in corn production on claypan soil fields in Missouri. Topsoil thickness is an indicator of soil productivity and crop yields for claypan soils (Gantzer and McCarty, 1987). Varying N rate based on topsoil depth potentially increases N use efficiency and corn yield, and reduces N losses (Kitchen et al., 1998). Soil profile electrical conductivity (EC) measurements provide an accurate and efficient way of mapping topsoil depth in claypan fields (Kitchen et al., 1999). Soil EC mapping has also been used in other regions to help farmers assess soil quality and apply precision agricultural practices (Doerge, 2000). A unique feature of this study was that it evaluated the economic and environmental benefits of VRT using topsoil depth data measured by soil EC. It builds on earlier research that developed variable N application based on EC-measured topsoil depth for claypan soils by Kitchen et al. (1995; 1998; 1999). Another unique contribution of this research was the simultaneous assessment of variable rate application of N and lime. Low soil pH in claypan soils limits crop uptake of nutrients, and liming acidic soils improves nutrient use efficiency by crops (Adams and Martin, 1984).

This study used a combination of field-measured variability and simulation procedures to evaluate profitability and potential improvement in water quality of variable rate N and lime applications for four claypan soil fields in Missouri. Specific objectives were: (1) to evaluate whether VRT of N (based on topsoil depth) and lime (based on grid-sampled soil pH) are more profitable than URT in claypan soil fields; (2) to compare the water quality effects of VRT and URT; and (3) to examine the effects of variation in topsoil depth and soil pH on the profitability and water quality benefits of VRT. This analysis incorporated three basic assumptions. First, topsoil depth and soil pH were assumed to be the major factors that affected corn yield. There are other factors that could significantly affect corn yield such as insects, diseases, and drainage problems. However, incorporation of all factors would call for much more complicated analyses in terms of analytical framework and field experimental design. This study focuses on the relationship between corn yield, and topsoil depth, soil pH, N and lime applications, and does not consider the impacts of other yield limiting factors mentioned above, that is, the outcome of this analysis excluded other factors that may have effects on corn yield. Second, stochastic weather conditions were assumed to be average to better-than-average for corn production during the growing season. This assumption was implicitly incorporated into a function relating corn yield to topsoil depth developed by Kitchen et al. (1995). Subsequent investigations have shown that this general functional relationship holds for corn production for most years when crop water needs are insufficient (Kitchen et al., 1999). Third, this study assumed that variability of soil properties could be accurately detected and that application of N and lime could be made without error.

Materials and methods

Agronomic data

Four representative claypan soil fields, located in north central Missouri, were used for this study. The predominant soils in these fields include Mexico silt loam, Mexico silt clay loam, and Putnam silt loam. Claypan soils are usually low in natural fertility and soil pH, and cover about 4 M ha in the Midwestern United States (Alberts et al., 1993). Topsoil depth was estimated for each field based on measurements of bulk soil EC. EC is highly correlated with topsoil depth above the claypan (Doolittle et al., 1994; Kitchen et al., 1999). Collection of EC data was done with a mobile EM38 measurement system that included an all-terrain vehicle, a wooden trailer carrying the EM38 meter at 200 mm above the ground surface, a differentially corrected (within 3 m of actual) Global Positioning System (GPS) receiver, and a computer for data acquisition (Kitchen et al., 1996). EC measurements were collected on 20 m transects on 1 sec intervals, traveling at a speed of about 15 km/hr. The relationship between EC and topsoil depth developed by Kitchen et al. (1999) was used to convert EC measurement into soil depth. Soil pH and Neutralizable Acidity (N.A.) were obtained by analyses of soil samples collected on a 30 m grid (approximately 11 samples per ha).[1] Kriging method was used to interpolate topsoil depth, soil pH and N.A. for entire fields from the measured data at different scales as described above.

In this study, management units for variable N and lime application in each field were 18.3 m cells. Such cell size is compatible with the operation scale of most farming machinery for variable rate applications in Missouri. Specifically, each field was divided into 18.3 m cells and information about topsoil depth, soil pH, and N.A. for each cell were interpreted from the interpolated field date mentioned above. The cell information was then used to implement the URT and VRT strategies discussed below. Table 1 summarizes the information for the four sample fields. The four fields vary by size, topsoil depth, N.A., and soil pH. Topsoil depth is more variable in Fields 2 and 4 than in Fields 1 and 3. Soil pH is more variable in Field 1 than in the other three fields. N.A. is more variable in Fields 1 and 4 than in Fields 2 and 3.

Table 1. Summary data for the four sample fields

			Topsoil depth (mm)		Soil pH		N.A. (meq/100g)	
Field	# of cells	Size (ha)	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
1	1,032	35.6	425	150	5.94	0.52	2.32	1.36
2	343	13.4	371	211	6.86	0.33	0.42	0.59
3	611	22.3	405	117	6.84	0.21	0.33	0.46
4	837	28.3	345	169	5.90	0.33	1.87	1.01

N rate determination

Target corn grain yield with VRT was based on the following linear-plus-plateau model developed by Kitchen et al. (1995):

$$Y_i^T = 6{,}083 + 5.53X_i \tag{1}$$

with the maximum Y_i^T of 11,476 kg/ha, where i is the index for cells in a corn field; Y_i^T is target corn yield in kg/ha for cell i; X_i is topsoil depth to claypan in mm for cell i. This equation applies to non-irrigated corn on claypan soils and was used to establish a target corn yield and select an N application rate with side-dress or pre-plant application as follows:

$$N_i = 0.016Y_i^T \text{ for side-dress N application, or} \tag{2a}$$

$$N_i = 0.022Y_i^T \text{ for pre-plant N application,} \tag{2b}$$

where N_i is N rate in kg/ha for cell i; and Y_i^T is target corn yield in kg/ha for cell i determined from Equation (1). The N rates given by Equations (2a) and (2b) were assumed to give the needed N per unit of yield. They are unique because of differences in N use efficiency with timing. N rate for each cell was determined based on Equation (2a) or (2b).

Two uniform N application strategies were evaluated. Strategy 1, called URT-N1, determined the uniform N rate for a field by substituting the average topsoil depth of selected cells for a field into Equation (2a) if N was side-dressed, or Equation (2b) if N was pre-plant broadcast. The selected cells were those whose topsoil depth was within the upper 95 percentile of topsoil depth in the field. While farmers may not know topsoil depth variation in a field, this strategy represented an approach where farmers apply N to match the majority soils of fields. As such, it mimics an "insurance application" strategy, where N would be a non-limiting factor for corn growth (Schepers and Mosier, 1991; Goos and Prunty, 1990). Strategy 2, called URT-N2, was 191 kg/ha of N applied broadcast before planting. The N rate for strategy 2 was typical for corn production in this area, and has been used as the "conventional" N rate in claypan soil field experiments for the past decade (Kitchen et al., 1995; 1998).

Lime rate determination

While the optimal soil pH for corn growth is between 5.5 and 7.5, maintaining soil pH in the range of 6.1 and 6.5 is advisable (Buchholz et al., 1983). Liming for maintaining soil pH requires frequent soil monitoring because soil pH can decline below 5.5 in a matter of a few years (Buchholz et al., 1983; Fisher, 1969).

The Effective Neutralizable Material (ENM) needed for cell i was based on soil pH and was determined by (Buchholz et al., 1983):

$$ENM_i = 448\left[N.A._i - \frac{N.A._i}{41.425 - 10.307\text{pH}_i + 0.629\text{pH}_i^2}\right] \text{ if pH}_i < 6.1, \quad \text{or}$$
$$= 0 \text{ otherwise,} \tag{3}$$

where ENM_i was ENM in kg/ha required to increase soil pH to between 6.1 and 6.5 in cell i, $N.A._i$ is neutralizable acidity in meq/100g for cell i, and pH_i is soil salt pH for cell i. The lime rate in t/ha was calculated by the following equation:

$$\text{Lime rate} = 2.204\ (\text{required ENM rate})/(\text{ENM of the lime}). \quad (4)$$

A uniform lime rate, which was used across the whole field, was determined by substituting the field average soil pH and average N.A. into Equation (3). Each cell then received this uniform lime rate.

Expected corn yield

Expected corn yields for VRT and URT-N1 were determined by the following equation.

$$Y_i^E = (\text{expected corn yield associated with cell N rate})\, SUFF_i^{\text{pH}}, \quad (5)$$

where Y_i^E is expected corn yield in kg/ha for cell i and

$$SUFF_i^{\text{pH}} = \begin{Bmatrix} 1.0 \text{ } \mathit{if}\ 5.5 \le \text{pH}_i \le 7.5 \\ 0.16\text{pH}_i + 0.12 \text{ } \mathit{if}\ 5.0 \le \text{pH}_i \le 5.5 \\ 0.446\text{pH}_i - 1.31 \text{ } \mathit{if}\ 2.9 \le \text{pH}_i \le 5.0 \end{Bmatrix}, \quad (6)$$

which was the soil pH sufficiency for cell i (Kiniry et al., 1983). Soil pH in claypan soils seldom exceeds 7.3. Over-application due to uniform lime application based on Equation (3) was considered negligible and ignored in this analysis.

Expected corn yield for cell i with variable N and lime rates was the same as the target corn yield given in Equation (1). Since VRT of N theoretically results in an optimal N rate, the first term in Equation (5) was the same as the target corn yield in Equation (1). The second term in Equation (5) equals one because variable rate application of lime gives corn plants an optimal soil pH environment.

Uniform N and lime application resulted in under-application of N and lime in some cells and over-application of N and lime in others. When N was under-applied, expected corn yield was:

$$Y_i^{\text{under}} = (N_u/0.016) SUFF_i^{\text{pH}} \text{ for side-dress, or} \quad (7a)$$

$$Y_i^{\text{under}} = (N_u/0.022) SUFF_i^{\text{pH}} \text{ for pre-plant,} \quad (7b)$$

where Y_i^{under} was expected corn yield in kg/ha for cell i when N was under-applied; and N_u was uniform rate of N applied.

When N was over-applied, the expected corn yield was:

$$Y_i^{\text{over}} = (N_i/0.016) SUFF_i^{\text{pH}} \text{ for side-dress, or} \quad (8a)$$

$$Y_i^{\text{over}} = (N_i/0.022) SUFF_i^{\text{pH}} \text{ for pre-plant,} \quad (8b)$$

where Y_i^{over} was expected corn yield for cell i when N was over-applied; and N_i was optimal N rate for cell i given by Equation (2a) or (2b).

If lime was under-applied to a cell, the soil pH in the cell could not reach 6.1. ENM_{added} was the ENM actually added to the soil and ENM_{desired} was the ENM that was required to increase soil pH to between 6.1 and 6.5. The deficit of ENM when lime was under-applied was:

$$ENM_{\text{deficit}} = ENM_{\text{desired}} - ENM_{\text{added}}. \tag{9}$$

$N.A._{st}$ denoted the soil test N.A. before adding ENM, and $N.A._{\text{corrected}}$ denoted the soil N.A. change after adding ENM. Hanson (1977) developed the following relationship between added ENM and $N.A._{\text{corrected}}$:

$$N.A._{\text{corrected}} = ENM_{\text{added}}/448. \tag{10}$$

The new N.A. was:

$$N.A._{\text{new}} = N.A._{st} - N.A._{\text{corrected}}. \tag{11}$$

Substituting ENM_{deficit} and $N.A._{\text{new}}$ into Equation (3) yields:

$$ENM_{\text{deficit}} = 448\left[N.A._{\text{new}} - \frac{N.A._{\text{new}}}{41.425 - 10.307\text{pH} + 0.629\text{pH}^2}\right] \tag{12}$$

Equation (12) can be solved for actual pH. Since Equation (12) is quadratic, there were two solutions for pH. Only one value was realistic and was used to calculate soil pH sufficiency specified by Equation (6).

The uniform N rate under URT-N2 was 191 kg/ha as previously discussed. Historically, the highest corn yield on a county-wide basis for the study area is about 8,150 kg/ha (MASS, 1992–1998). This corn yield was used as the expected corn yield for URT-N2. Lime rate was the same as under URT-N1.

Economic analysis

Economic optimization and partial budgeting are the most common methods used in the economic evaluation of VRT. Constrained maximization of net return is an economic criterion based on the principle that farmers maximize net returns subject to various resource constraints (Prato and Kang, 1999; Qiu and Prato, 1999). Net return is maximized when marginal revenue equals marginal cost of production. Although this criterion is economically sound, it may not be easy to follow in precision agriculture, because farmers cannot control stochastic factors, such as weather. In addition, it is difficult to determine the marginal value of information, which is at the core of precision agriculture (Swinton and Lowenberg-Deboer, 1998). Partial budgeting calculates changes in profit due to changes in inputs. Although it does not guarantee maximum net return, it is easy for farmers to implement and is well suited for economic evaluation of VRT (Swinton and Lowenberg-Deboer, 1998).

In partial budgeting, net return due to a change in a farming system equals gains minus losses resulting from the change. In this study, gains resulted from the increased revenue due to potentially higher corn yields and/or reduced costs from lower N and lime application rates, and losses resulted from the increased costs of doing variable rate application of N and lime. Mathematically, change in field-level net return, or profit in switching from URT to VRT was determined as:

$$\begin{aligned}\Delta\pi = P_C(E(Y_V) - E(Y_U)) - P_N(\overline{N}_V - \overline{N}_U)\\ - P_L(\overline{L}_V - \overline{L}_U)A - \text{extra VRT costs}\end{aligned} \tag{13}$$

where $\Delta\pi$ was the profit difference between VRT and URT in \$/ha; $E(Y_V)$ was the expected corn yield for the field in kg/ha with VRT; $E(Y_U)$ was the expected corn yield for the field in kg/ha with URT; $\overline{N}_V$ was the average N rate for the field in kg/ha with VRT; $\overline{N}_U$ was the average N rate for the field in kg/ha with URT; $\overline{L}_V$ was the average lime rate for the field in t/ha with VRT; $\overline{L}_U$ was the average lime rate for the field in t/ha with URT; P_C is price of corn in \$/kg; P_N was the price of N in \$/kg; P_L was the price of lime in \$/t; A equaled $(r)/(1-(1+r)^{-n})$ as described in Equation (14) below; and extra costs for VRT equaled the additional annual costs in services for adopting VRT relative to URT in \$/ha.

Here we assumed the cost of VRT services included the cost for variable rate N and lime application, soil EC mapping and testing for soil pH and N.A. For this comparison, we used a soil pH and N.A. sample density of 1 sample/ha for VRT, and 1 sample per 8 ha for URT. The sampling density of 1 sample/ha was approximately the scale of grid soil sampling for VRT used by farmers in the Midwestern United States. A previous analysis on one of these study fields indicated that sampling at 1 sample/ha grid captured the spatial dependence of soil pH and could be effectively used to create a soil pH map (Birrell et al., 1996). Costs incurred over several years, such as EC mapping and soil sampling, were annualized using the following net present value annuity formula:

$$\text{Annualized cost} = \frac{rI}{1-(1+r)^{-n}}, \tag{14}$$

where I is the cost of information or farming activities, r is the discount rate, and n is the useful lifetime of information or farming activities in years (Lowenberg-DeBoer and Swinton, 1997).

Soil sampling for lime application is generally repeated every three or four years in Missouri. For simplicity in this evaluation, it was assumed that these operations were done once every three years. Therefore, the costs of VRT of lime were annualized over a three-year period. It was assumed that soil EC mapping was needed only once, and therefore, its cost was annualized over a 10-year period.

The discount rate (r) was estimated based on the average rate of return on a portfolio of common stock, because stock investment has a risk level similar to agriculture (Lowenberg-DeBoer and Swinton, 1997). The average rate of return was 11.2% for large company stock and 12.4% for small company stock from 1926 to 1998 (Ibbotson Associates, 1999). Therefore, the discount rate used in Equation (14) was 11.8%, the average of 11.2%, and 12.4%. Table 2 gives the custom service charges and the annualized cost of services calculated using Equation (14). Extra cost for variable rate N application was \$2.47/ha (cost item 1 minus cost item 2 in Table 2). Extra cost related to soil pH and N.A. testing and sample handling was \$1.18/ha (sum of cost items 5 and 6, minus sum

Table 2. Custom charges and annualized costs of agricultural services in Missouri used to compare VRT and URT, 2000

Item no.	Services	Custom charge	Annualized cost[a]	Duration (years)
1.	Variable rate N application	\$11.12/ha[b]	\$11.12/ha	1
2.	Uniform rate N application	\$8.65/ha[b]	\$8.65/ha	1
3.	Variable rate lime application	\$4.00/t[b]	\$1.66/t	3
4.	Uniform rate lime application	\$3.50/t[b]	\$1.45/t	3
5.	Soil testing for pH and N.A. with VRT	\$2.70/sample[c]	\$1.11/ha[f]	3
6.	Sample handling for pH and N.A. with VRT	\$0.60/sample[d]	\$0.25/ha[f]	3
7.	Soil electrical conductivity mapping	\$19.77/ha[e]	\$3.46/ha	10
8.	Soil testing for pH and N.A. with URT	\$2.70/sample[d]	\$0.15/ha[g]	3
9.	Sample handling for pH and N.A. with URT	\$0.60/sample[c]	\$0.03/ha[g]	3

a. A discount rate of 11.8% is used to calculate annualized costs.
b. Charges are the current prices quoted by a local precision agriculture service company.
c. Soil fertility test charge is \$9/sample (Soil Testing Lab, University of Missouri-Columbia). Soil pH and N.A. analyses account for approximately 30% of the testing costs.
d. Assumes 15 minutes are needed to collect and package a sample. Labor is \$8/h. Similarly, analyses of soil pH and N.A. account for 30% of the total handling cost.
e. Estimated based on personal communication with N. R. Kitchen and precision agriculture service providers.
f. Soil testing is conducted at a density of 1.012 ha/sample with VRT.
g. Soil testing is conducted at a density of 8.09 ha/sample with URT.

of cost items 8 and 9 in Table 2). Extra cost of variable rate lime application in \$/ha was lime rate with VRT (t/ha) times \$1.66/t, minus lime rate with URT (t/ha) times \$1.45/t.

N price was \$0.397/kg, based on anhydrous ammonia (82% N). The corn price used was \$0.102/kg. Both prices are five-year averages in Missouri for the 1994–1998 period (NASS, 1995–1999). The price of lime with an ENM of 386 was \$7/t, as quoted by central Missouri lime dealers in 1999.

Water quality indicator

N was assumed to be the only factor that affected the water quality benefits. Variable N application rate was the optimal N rate for achieving an optimal corn yield. N rates that exceed the optimal rate have higher potential for N leaching (Pratt, 1979). Therefore, over-application of N in cells of a field was assumed to increase potential leachable N. Cells in which N was under-applied were assumed to have approximately the same potential leachable N as the optimal N rate. The difference in potential leachable N (DPLN) between VRT and URT was treated as an indicator of the potential water quality benefits of VRT. The difference in potential leachable N in a cell between VRT and URT was determined as:

$$\begin{aligned} DPLN_i &= N_{Vi} - N_U, \ \text{if } N_{Vi} < N_U, \qquad \text{or} \\ &= 0, \qquad\qquad \text{if } N_{Vi} \geq N_U, \end{aligned} \tag{15}$$

where $DPLN_i$ was the difference in potential leachable N in kg/ha for cell i, N_{Vi} was the variable N rate in kg/ha for cell i, and N_U was the uniform N rate in kg/ha for the field. The more negative $DPLN_i$, the greater the potential water quality benefits of VRT. Even though it implicitly implies that VRT has better water quality impact than URT, the indicator helps to evaluate how much VRT was better off, compare water quality impacts across fields, and assess the water quality impacts as a function of spatial variability in topsoil depth in a field.

Sensitivity analysis

Sensitivity analysis was performed to evaluate how spatial variability affected the profitability and water quality benefits of VRT relative to URT. Specifically, impacts of variations in topsoil depth and soil pH in a field were evaluated. In order to reduce analytical complexity, impacts of variation in N.A. were not considered because of the strong correlation between soil pH and N.A. Using the crop response algorithms and economic conditions outlined above, a sensitivity analysis was performed on the simulated topsoil depth and soil pH. Field 1 soil conditions were used as a basis for simulation. This field was 35.6 ha and contained 1,032 cells. When topsoil depth was simulated, soil pH and N.A. were held constant at their values for the field. Similarly, when soil pH (with N.A.) was simulated, topsoil depth was held constant at their values for Field 1.

@RISK (Palisade Corporate, 1996) was used to fit the distributions and simulate topsoil depth and soil PH. @RISK is a risk analysis and simulation software package that combines the power of Monte Carlo simulation and the convenience of spreadsheet models. Risk analysis in @RISK is a quantitative method that seeks to determine the outcomes of a decision as a probability distribution. In general, risk analysis with @RISK encompasses four steps: developing a model, identifying uncertainty, analyzing the model with simulation, and making a decision. It has been widely used in risk and decision analysis in the areas of finance and engineering (www.palisade.com).

The best fitting distributions were loglogistic for topsoil depth and triangular for soil pH. The advantage of loglogistic and triangular distributions was that they do not generate negative values when the parameters were appropriately adjusted. Wang (2000) gave a detailed description of the statistical tests for goodness-of-fit. The following regression equation for Field 1 was used to estimate N.A. from the simulated soil pH values:

$$N.A. = 17.42 - 2.53^{*}\text{pH}, \tag{16}$$

with $R^2 = 0.92$. Simulated soil pH and estimated values of N.A. were used to determine ENM recommendation rates.

Each simulation generated 100 values for topsoil depth, soil pH and N.A. that had the same underlying distributional parameters for each cell as found in Field 1. Simulated values were used to generate means and standard deviations for the profitability and *DPLN* of VRT. This procedure was used to further examine the effects of the means or standard deviations of topsoil depth and soil pH on the profitability and water quality benefits of VRT. The sensitivity analysis only compared URT-N1 to VRT.

Results and discussion

Expected corn yield, N and ENM rates for VRT, URT-Nl, and URT-N2 for the test fields are presented in Table 3. UTR-N2 was solely a pre-plant practice, therefore no side-dress of URT-N2 was included in the evaluation results. Expected corn yield was higher with VRT than with URT-N1 in all four fields and was higher with VRT than with URT-N2 for Fields 1 and 3. Average N rates were lower with VRT than with either URT N application strategy. ENM rates were higher for Fields 1, 2, and 3 and lower for Field 4 with VRT than with URT. The two URT N application strategies used the same ENM application method. In Fields 2 and 3, ENM application was required with VRT for small portions of the fields but was not required with URT. Under VRT, applied ENM improved corn yield, and therefore, response to N input.

Economic and potential water quality impacts of VRT relative to URT for the four sample fields are given in Table 4. Even with additional application costs, VRT was more profitable than URT-N1 for all four fields. Higher profits with VRT resulted primarily from increased corn yield as reported in Table 3. There was N cost saving, but it was very minimal. Profits with VRT were slightly higher with pre-plant N application than with side-dress application because the former resulted in greater N cost saving. Compared to URT-N2 with pre-plant application, VRT was more profitable for Fields 1 and 3 and less profitable for Fields 2 and 4. Although substantial N cost saving was expected, revenue with VRT for Fields 2 and 4 decreased due to the fact that corn yield with URT-N2 was identical for all fields.

Table 3. Expected corn yield, N and ENM rates for four sample fields under different N and lime application strategies

	Expected corn yield kg/ha	N rate Pre-plant kg/ha	 side-dress kg/ha	ENM rate[a] kg/ha	ENM area[b] %
Field 1					
VRT	8428	181	136	647	66
URT-N1	8184	183	137	622	100
URT-N2	8152	191	—	622	100
Field 2					
VRT	8134	175	131	15	3
URT-N1	7701	176	132	0	0
URT-N2	8152	191	—	0	0
Field 3					
VRT	8322	179	134	4	1
URT-N1	8115	180	135	0	0
URT-N2	8152	191	—	0	0
Field 3					
VRT	7983	172	129	473	67
URT-N1	7682	173	130	505	100
URT-N2	8152	191	—	505	100

a. Lime (ENM) rate is the same for URT-N1 and URT-N2.
b. Lime (ENM) area is the percentage of the field to which lime is applied.

Table 4. Profitability and potential water quality impact (DPLN) of VRT relative to URT for four sample fields[a]

		Field 1		*Field 2*		*Field 3*		*Field 4*	
	Units	URT-N1	URT-N2	URT-N1	URT-N2	URT-N1	URT-N2	URT-N1	URT-N2
Change in revenue	$/ha	24.86	28.05	43.98	−1.90	21.03	17.22	30.59	−17.22
Change in N cost									
Pre-plant	$/ha	−0.79	−3.90	−0.67	−6.35	−0.32	−4.77	−0.72	−7.66
Side-dress	$/ha	−0.57	—	−0.57	—	−0.20	—	−0.54	—
Change in lime cost	$/ha	0.40	0.40	0.25	0.25	0.05	0.05	−0.52	−0.52
Extra cost of VRT	$/ha	8.10	8.10	7.26	7.26	7.17	7.17	7.41	7.41
Profitability of VRT									
Pre-plant	$/ha	17.15	23.45	37.14	−3.06	14.13	14.77	24.42	−16.45
Side-dress	$/ha	16.93	—	37.04	—	14.01	—	24.24	—
DPLN									
Pre-plant	kg/ha	−7	−13	−11	−21	−5	−14	−8	−22
Side-dress	kg/ha	−5	—	−8	—	−4	—	−6	—

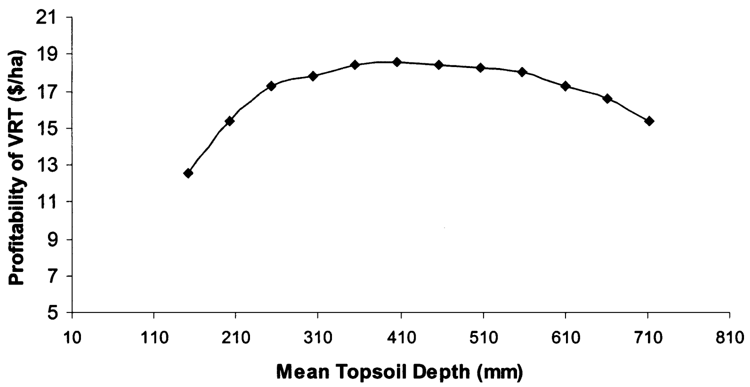
a. Negative values indicate VRT is less profitable, has lower cost or has lower potential leachable N than URT, and vice versa for positive values.

DPLN values were negative in all fields as expected (Table 4). This implied VRT eliminated excessive N application associated with URT in some portions of fields which resulted in water quality benefits. With URT-N1, the *DPLN* values were lower with pre-plant than with side-dress N application, because pre-plant application reduced N use more than side-dress application under VRT (Table 3). In general, side-dress application used less N than pre-plant application and, therefore, lowered the potential for water quality degradation. Among the pre-plant applications, the *DPLN* values were much lower with URT-N2 than URT-N1, which implied VRT had greater water quality impacts over URT-N2 than over URT-N1. The *DPLN* values also varied across fields. In general, VRT resulted in better water quality impacts in Fields 2 and 4 than in Fields 1 and 3.

Results in Tables 1, 3, and 4 indicate that variations in topsoil depth and soil pH were important determinants of corn yield variation in claypan soil fields, and have significant impact on the profitability and water quality benefits of VRT. The greater the standard deviation of topsoil depth in a field, the higher the potential profitability and water quality benefits (lower *DPLN)* of VRT relative to URT-N1. Also, the greater the mean topsoil depth, the higher the potential profitability and lower the water quality benefit (higher *DPLN)* of VRT relative to URT-N2. There was no relationship between profitability of VRT and soil pH, because the effect of topsoil depth dominated over the effect of soil pH. Relationships between profitability for VRT and topsoil depth, and between water quality benefits for VRT and topsoil depth were different relative to URT-N1 and URT-N2, because the uniform N rates under URT-N2 were the same for all four fields while N rates were variable and calculated from field data for URT-N1.

Based on the estimated parameters of the loglogistic and triangular distributions, @RISK (Palisade, 1996) was used to simulate topsoil depth and soil pH values for each cell in Field 1. Topsoil depth affected the profitability and water quality benefits obtained

(A)



(B)

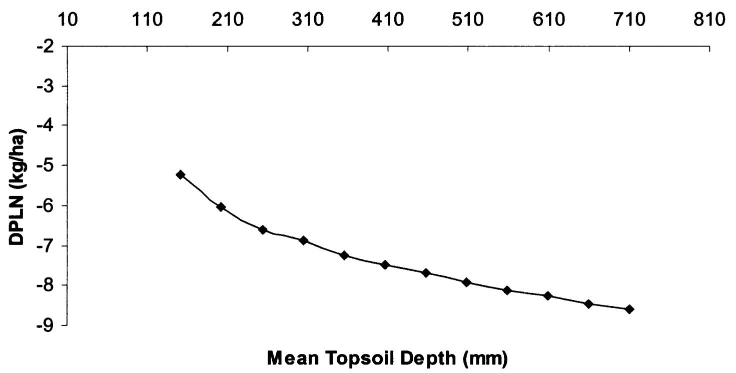


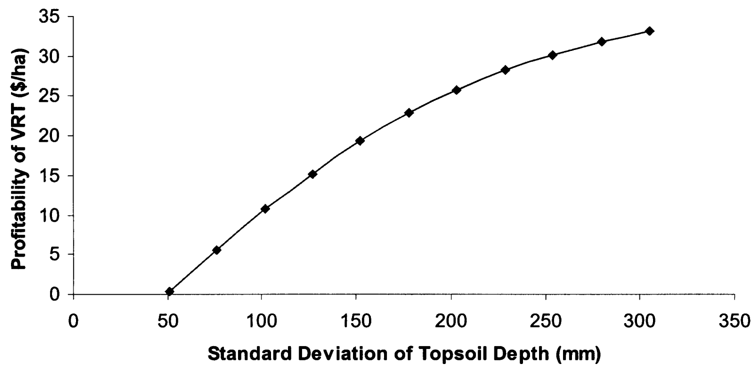
Figure 1. Impact of mean of topsoil depth on profitability (A), and DPLN values (B), of VRT relative to URT-N1.

with VRT. As shown in Figure 1(A), profitability of VRT increased from 150 to 400 mm of topsoil depth, and then decreased as topsoil was >500 mm. Water quality benefits of VRT increased as the mean topsoil depth increased (Figure 1(B)). As mean topsoil depth increased, more N was applied to achieve higher corn yield with both VRT and URT. The outcome was a greater difference in potential leachable N at the field scale, and the likelihood of achieving water quality benefits with VRT (Figure 1(B)).

As the standard deviation of topsoil depth increased, profitability of VRT increased (Figure 2(A)) and *DPLN* decreased (Figure 2(B)). Profitability and water quality benefits of VRT were more sensitive to changes in the standard deviation than in the mean of topsoil depth.

Economic impacts of the mean and variation in soil pH are shown in Figure 3. There was a sharp decrease in the profitability of VRT above soil pH of 6.1 (Figure 3(A)). This occurred because no lime was applied with URT when the mean soil pH was greater than or equal to 6.1. Profitability of VRT did not show a clear decreasing relationship with

(A)



(B)

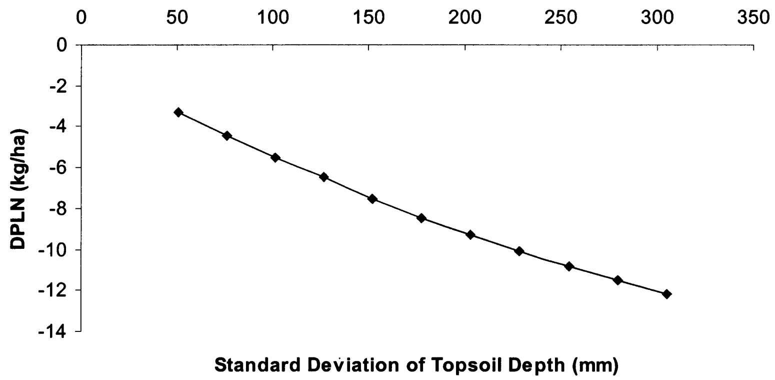


Figure 2. Impacts of standard deviation of topsoil depth on profitability (A), and D-LN values (B), of VRT relative to URT-N1.

respect to increasing soil pH, because VRT does not necessarily reduce ENM rates at the field scale. Profitability of VRT was more sensitive to changes in the standard deviation of soil pH (Figure 3(B)). Greater variation in pH produced higher potential profitability with VRT relative to URT. These results are consistent with Sawyer's (1994) observation that spatial variation in field properties was one of the primary factors that affected the profitability of VRT.

Figure 4 shows how changes in corn, N, and lime prices affect profitability of VRT. There was a monotonic relationship between profitability of VRT and price fluctuations. Profitability of VRT increased as corn price increased (Figure 4(A)). Profitability of VRT only slightly increased as N price increased (Figure 4(B)). Profitability of VRT gradually decreased as lime price increased (Figure 4(C)). Thus, profitability of VRT was more sensitive to changes in corn price, and less sensitive to changes in N and lime prices. VRT was profitable for all evaluated price scenarios.

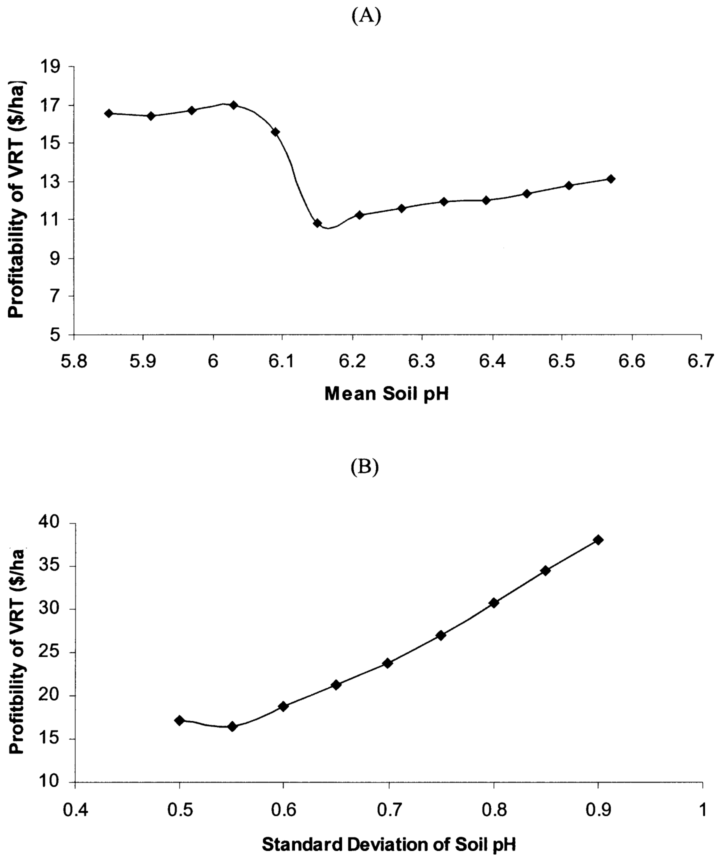


Figure 3. Impacts of mean (A), and standard deviation (B), of soil pH on profitability of VRT relative to URT-N1.

Summary and conclusions

This study analyzed profitability and water quality benefits of VRT relative to two URT strategies (URT-N1 and URT-N2) in four claypan soil fields in Missouri. Generally, VRT appeared to be economically better than URT-N1, but VRT did not result in uniformly higher profit than URT-N2. Profitability of VRT relative to uniform N application varied from field-to-field, and depended on the uniform N strategy to which it was compared, and within-field variation in soil properties. Water quality benefits of VRT also varied by URT strategy. VRT had greater water quality benefits when compared to URT-N2 than to URT-N1. Water quality benefits of VRT varied across fields. Sensitivity analysis indicated that the profitability and water quality benefits of VRT increased with greater variability in topsoil depth and/or soil pH, but were more sensitive to changes in standard deviation than the mean of these variables.

This study has several important implications for the use of VRT on claypan soil fields in the Midwest. First, while VRT has the potential to improve water quality, it does not automatically result in uniformly higher profits than URT. Second, the method of N

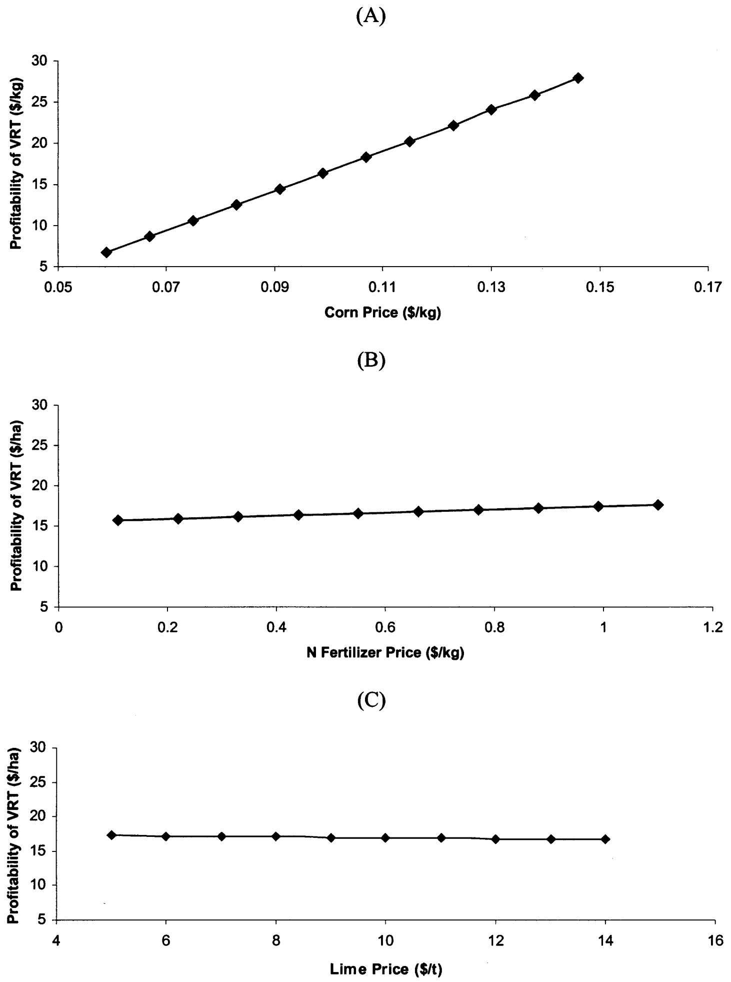


Figure 4. Impacts of corn (A), N fertilizer (B), and lime prices (C), on profitability of VRT relative to URT-N1.

application (side-dress or pre-plant broadcast) affected the profitability and water quality benefits of VRT.

This type of investigation inherently has limitations. It implicitly assumed average to better than average weather conditions for corn production. Corn yield differences between VRT and URT may not be the same with less favorable growing conditions. Other uncertainties in agricultural production (e.g., weed and insect infestation, and fluctuating grain and fertilizer prices) also affect the profitability of VRT. It is difficult to account for all of these stochastic factors in evaluating the relative profitability of VRT. Future studies should attempt a more comprehensive treatment of such uncertainties. This study did not consider the spatial correlation of soil characteristics when evaluating their distributions. We suggest that future studies need to incorporate the impact of spatial correlation of soil characteristics on corn yield and profitability of VRT. This analysis combined real field conditions with simulated corn crop response to evaluate the economic and environmental benefits of VRT. We are currently conducting other studies to evaluate benefits of the variable rate N strategy for corn production using large-scale field trial data collected over seven years.

Note

1. Neutralizable acidity test is included in the standard soil test package implemented by the Missouri Cooperative Extension Service, University of Missouri-Lincoln University. See Brown and Rodiguez (1983) for details. The Cost of testing neutralizable acidity is also included in the cost of the soil test in the latter analysis.

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