Journal of the Arkansas Academy of Science

Volume 56 Article 20

2002

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Abstract

The purpose of this study is to examine the profitability of variable rate phosphorus application on a rotation of rice (*Oryza sativa*) and soybeans (*Glycine max*) on fields comprised of clay and silt loam soils. Phosphorus was chosen because 1) farmers have recently been advised of the benefit of phosphorus applications on rice as well as soybeans, 2) recommended phosphorus application rates vary greatly between clay and silt loam soils and across rice and soybeans, and 3) the residual effects of phosphorus applications in a crop rotation affect the appropriateness of variable rate technology (VRT).

A three phase simulation, regression and mathematical optimization analysis was conducted to determine within a ten year planning horizon the conditions under which the profitability of variable rate phosphorus applications exceeded the profitability of uniform rate technology. Results showed that in general, VRT is not profitable when fields are comprised of only the three studied silt loam soils. However, VRT was found to be profitable in most cases when even small percentages of clay were added to the soil mix in the field. Adoption will likely also be a function of farm size. Farmers earning relatively small returns to VRT on a small area are not as likely to adopt the technology as larger operations with similar per hectare returns.

Introduction

The silt loam, sand and clay soils of the Arkansas delta are home to 4.4 million acres of irrigated cropland. Major irrigated crops include rice, cotton, and soybeans (AASS, 1999). Of these crops, rice and soybeans are often grown in rotation so that residual effects of management practices from one year to the next may be important. In the past, phosphorus was not generally recommended for rice grown in Arkansas for two reasons. First, the availability of phosphorus under the flooded conditions associated with upland rice is difficult to predict, it is very common for flooded soils to provide adequate levels of phosphorus for rice as the soils become reduced causing the dissolution of iron (III) and manganese (IV) phosphate minerals (Hossner and Baker, 1988). Second, residual phosphorus levels from the soybean portion of the rotation are already adequate for rice production on many soils (Beyrouty et al., 1991). Recent research, however, has shown that applied phosphorus (P_2O_5) can improve the chances of attaining optimal rice yields on alkaline silt loam soils (Wilson et al, 1999). Yet, a similar recommendation has not been made for clay soils. Further, while adequate levels of phosphorus are advantageous, excess phosphorus in the soil may indirectly decrease yields due to micronutrient imbalances. This new information suggests that phosphorus management in rice production may be beneficial, especially when rice fields are comprised of both silt loam and clay soil.

Variable rate technology (VRT) can be defined as changing the application rate of an input across a field so as to meet nutrient requirements for production. By contrast, uniform rate technology (URT) ignores spatial variation in input requirements and leads to a single rate input application on the entire field. Much economic research has focused on VRT in recent years (see Lambert and Lowenberg-DeBoer (2000) for a compilation of economic studies). Some VRT studies focused on single, monoculture crops such as cotton (Yu et al., 1999) and corn (English et al., 1999, 2001; Lowenberg-DeBoer, 1998; Roberts et al., 2000) or single nutrients such as nitrogen (English et al., 1998, 1999; LaRuffa et al., 2001; Taylor et al., 1998; Thrikawala et al., 1999) and phosphorus (Yang et al., 1999; Yu and Segarra, 1999). While the focus of these studies typically was on productive capacities or profitability, some studies also discussed environmental concerns (English et al., 1999; Prato and Kang, 1998). Many studies (e.g., Babcock and Pautsch, 1998; English et al., 1998; Lowenberg-DeBoer, 1998; Prato and Kang, 1998; Watkins et al., 1998) suggest that the economic feasibility of VRT is linked to the inherent spatial differences of soil properties within a field (i.e., texture, fertility, and water holding capacity). Economic feasibility requires that benefits of VRT are greater than all the costs associated with VRT. This condition usually holds only for a limited range of input cost to crop price ratios, a specified amount of soil quality variability within a field, or both.

The purpose of this study is to examine the impact of variable rate phosphorus in a rice and soybean rotation. The objective is to evaluate the profitability of variable rate phosphorus application in fields with various proportions of silt loam and clay soils. Other evaluation criteria, such as environmental concerns, are reserved for future study. This research thus addresses under what conditions variable rate phosphorus is economically viable for rice and soybean production in regions facing similar conditions as those modeled.

Materials and Methods

This study extends previous research efforts of VRT benefits in agricultural production (see Lambert and Lowenberg-DeBoer (2000) for full compilation). This study compares URT to VRT phosphorus applications in a 1:1 rice and soybean crop rotation. As in previous studies (English et al., 1999; Lowenberg-DeBoer, 1999; Prato and Kang, 1999; Yu and Segarra, 1999), biophysical simulation data and hypothetical field combinations of multiple soil series are used for analysis. Sensitivity analysis on input and crop prices is utilized to examine price effects on optimal phosphorus application rates and economic feasibility of VRT.

This section progresses by 1) describing assumptions made regarding producer behavior, 2) outlining the production environment, 3) presenting the simulation framework, 4) delineating the functional form of required response equations, and 5) outlining optimization procedures.

Study Assumptions.--Four assumptions are made. First, variable rate application of phosphorus on a given field involves the following processes. Geographical information system (GIS) software produces a prescription nutrient plan based on the results of soil sampling. Application equipment with variable rate controllers (many types are available, but all use similar methods) interprets the prescription nutrient plan and applies product at appropriate rates site specifically. Second, VRT technology and field variability are assumed to be such that VRT is accurate enough to spatially match nutrient requirements with actual applications. It is understood that today's technologies are precise only to engineering constraints of the width of the applicator boom currently 60-foot or 90-foot swaths and many fields are likely more variable than this. Thus said, results may suggest a greater return to VRT application than may currently be feasible on the hypothetical fields in this study. Third, application rates of all other inputs, (such as nitrogen for example) are applied on all soils at a constant (or uniform) recommended rate rather than at a variable rate. Finally, simulations reflect potential conditions in Arkansas County, Arkansas, a leading rice and soybean production area in the state, where four commonly found soils –Calloway (fine-silty, mixed, active, thermic Aquic Fragiudalfs), Calhoun (fine-silty, mixed, active, thermic Typic Glossaqualfs), Crowley (fine, smectitic, hyperthermic Typic Albaqualfs), and Sharkey (very-fine, smectitic, thermic Chromic Epiaquerts)–were selected for this study. Soil properties including physical, chemical, and cultural characteristics are assumed to be homogeneous throughout the soil series. These soils are often found scattered throughout any given field in Eastern Arkansas (USDA, SCS, 1972).

Production Environment.--The three silt loam soils, Calloway, Calhoun, and Crowley, are considered similar in natural fertility and yield potential. Generally low in organic matter and natural fertility, these soils are expected to respond well to fertilizers and lime with similar potential for yields across soils (USDA, SCS, 1972). The Sharkey clay soil may be characterized as medium in organic matter and high in natural fertility; however, under similar nitrogen management, rice yields are expected to be lower than on the silt loam soils (USDA, SCS, 1972). Further, Sharkey soil currently has a zero phosphorus application recommendation for rice in Arkansas. Applied phosphorus and yield are, therefore, expected to exhibit a positive correlation in silt loam soils and a negative correlation in clay soils.

Crop Simulation.--The Environmental Policy Integrated Climate, or EPIC, model can be used to simulate crop production, soil erosion, water quality aspects, environmental concerns and ramifications of management practice changes over multiple years under varying weather conditions (Mitchell et al, 1995). Rice and soybean production practices such as tillage, planting, spraying, irrigating, and harvesting were adapted from field practices listed in Arkansas crop production budgets (Windham, 1999a, 1999b) and simulated in EPIC over a thirty-year period. A 1:1 rice-soybean rotation, representative of Arkansas county producer practices was followed (Norman, R. J. Personal communication). While applications of all inputs other than phosphorus were held constant at recommended rates, simulation runs were generated on the four soils using 13 different phosphorus fertilizer rates ranging from 0 to 107.6 kg ha^{-1} on each crop over a thirty-year planning horizon. A wide range of application rates was used to be able to adequately estimate the impact of phosphorus on crop yields. Three general phosphorus management strategies were followed. In the first, phosphorus rates were varied over both rice and soybean portions of the production process. In the second, the recommended phosphorus rate (Windham, 1999a) was used on the rice portion of the rotation where high and low phosphorus rates were used on soybeans. In the third, the recommended phosphorus rate (Windham, 1999b) was used on the soybean portion of the rotation where high and low phosphorus rates were used on rice. These three strategies were used in an attempt to capture the carryover effects of nutrient applications for different crops. As a result, 39 phosphorus treatments were developed. Due to duplications, 2 strategies were discarded leaving 37 different treatment combinations. These 37 combinations were replicated on each of the four soils, producing 148 total treatments. Over the 30-year production period, EPIC generated 4,440 observations (or 2,220 each for rice and soybeans) on over two hundred production and environmental variables.

Functional Form of Response Equations.--While crop production is a function of many factors including weather, soil moisture, tillage, variety, pesticide, soil quality, and timing of practices, this study utilizes only a few of the over two hundred variables of the EPIC model to focus on the profitability of variable rate phosphorus. Here, yield of a given crop is a function of soil phosphorus, applied phosphorus, and total available water. Soil phosphorus available at the beginning of any period is a function of previous period levels of soil phosphorus, applied phosphorus, phosphorus runoff, and phosphorus uptake by the crop. Finally, phosphorus runoff in any given period is a function of current amounts of soil phosphorus, applied phosphorus, total available water, and crop uptake of phosphorus. The following generalized equations, assumed to include the same variables for both rice and soybean crops, are thus used to evaluate the profitability of phosphorus driven yields:

$$Yld_t = f(SP_t, AP_t, W_t) \quad (1)$$
$$SP_t = g(SP_{t-1}, AP_{t-1}, Runoff_{t-1}, UP_{t-1}) \quad (2)$$
$$Runoff_t = h(SP_t, AP_t, W_t, UP_t) \quad (3)$$

where *Yld* is yield, *SP* is soil phosphorus, *AP* is applied phosphorus, *W* is total available water, *Runoff* is phosphorus runoff, *UP* is crop uptake of phosphorus, and *t* designates the time period–a production year. Using data from EPIC runs with the different phosphorus application rates, parameters are estimated for equations 1 to 3 and used to solve for profit maximizing phosphorus applications on each of the four soil series.

Optimization Procedures.--Once estimated, equations 1 to 3 serve in a mathematical optimization program, General Algebraic Modeling System (GAMS) (Brooke et al., 1998) to maximize discounted net revenue over a ten-year planning horizon for each of the soils. Net revenue was a function of total revenue (crop price times yield) less costs of production (price of phosphorus times the amount of phosphorus applied), VRT custom hire plus all other production costs specified in the enterprise budgets of Windham (1999a,b). The ten-year planning horizon was chosen to evaluate any phosphorus carryover effect between rice and soybean.

To determine the profitability of VRT on fields with combinations of different soils, the following two scenarios were established for the ten-year planning horizon 1) maximize profit by choosing variable phosphorus application rates across soils within a field for rice and soybean (referred to as the VRT system) and 2) maximize profit when phosphorus application rates are fixed at uniform rates according to the soil most prevalent in the field (referred to as the URT system). Profitability is calculated by adding discounted net revenues (yield times price less cost of production) across the ten-year planning horizon. Further, these net revenues are adjusted for their time of occurrence by adjusting each year's net revenue as if these cash flows occurred all at the same time. This eliminates effects of cash flow timing across the different scenarios and is thus a preferred method of evaluation. The results are returns to the production of soybeans and rice as if all production had occurred today and are called the net present value (NPV). These are cumulative returns to land, management and risk over the planning horizon. A rice price of \$0.189 kg^{-1}, a soybean price of \$0.239 kg^{-1}, a phosphorus price of \$0.55 kg^{-1}, VRT costs of \$9.88 ha^{-1}, and a discount rate of 8.0 percent per annum were used. The VRT cost is the custom hire of variable rate phosphorus application on a field. In Arkansas, most custom application firms charge a flat fee per acre. The custom rate is not a function of within field soil variability (Daniels, M. Personal communication). Differences in NPV across the VRT and URT systems over the ten-year planning horizon were calculated to determine returns to VRT adoption on fields characterized by combinations of the three silt loam soils only and combinations of silt loam and clay soils.

Optimization runs in GAMS were performed using various price levels to determine the sensitivity of phosphorus application rates across soils. Four prices (current and five year low, high and average prices) were used for rice and soybeans. Three prices (five year low, high and average prices; in this case average and current prices were the same value) were used for phosphorus. Two values were used for the discount rate. This resulted in 96 different price/discount rate combinations. Using these 96 price combinations on all four soils generated 384 optimization runs in total.

Results and Discussion

Intermediate results of crop simulation and functional form are presented first. Subsequently, the optimization work in GAMS is presented and discussed to provide answers for the study objectives.

Crop Simulation.--The EPIC simulated yields were compared to actual farm yields reported for Arkansas County. EPIC soybean yields ranged from 1,211 kg ha^{-1} to 3,093 kg ha^{-1} and are similar to 1994-1998 average county yields reported for irrigated soybean (AASS, 1999). EPIC rice yielded between 4,338 kg ha^{-1} and 6,305 kg ha^{-1}. These yields are slightly lower than typical rice yields in Arkansas County from 1994 to 1998 (AASS, 1999). Applying too little or too much phosphorus with the wide range in application rates in the model may have affected these observed yields.

Functional Form of Response Functions.--EPIC generated panel data for over 200 variables with thirty annual observations each. A general linear model for panel data was used to estimate equations 1 to 3 (Hsaio, 1991). All equations were tested for heteroskedasticiy and serial correlation using procedures outlined in Greene (1995). The model was adjusted for heteroskedasticity (Greene, 1995). The estimated equations took the following functional forms:

$$Yld_t = f(C, SP_t, AP_t, W_t, SP_t^2, AP_t^2, W_t^2) \quad (4)$$

adj. R^2: Rice = 0.64 Soybean = 0.70

$$SP_t = g(C, SP_{t-1}, AP_{t-1}, Runoff_{t-1}, Yld_{t-1}) \quad (5)$$

adj. R^2: Rice = 0.87 Soybean = 0.89

$$Runoff_t = h(C, SP_t, AP_t, W_t, Yld_t) \quad (6)$$

adj. R^2: Rice = 0.71 Soybean = 0.82

where C is an intercept term and other variables are as defined above. Note that for equations 5 and 6, substituting *Yld* for EPIC's *UP* variable led to better results. Also, as expected (Mitchell et al., 1995), the yield equation 4 for both rice and soybeans exhibited a quadratic functional form. Equations 5 and 6, the soil phosphorus and phosphorus runoff equations, respectively, showed a linear fit as expected from previous research (Daniel, T. Personal communication). Many of the parameter estimates were significant at the 99 percent confidence level, with signs and magnitudes of all coefficients as expected. Detailed results are available from the authors upon request.

Optimization.--First, the phosphorus application rates that maximize NPV for the VRT system are presented. Subsequently, returns to the adoption of VRT are assessed by comparing URT to VRT phosphorus applications on fields in two ways. First a field is assumed to be composed of combinations of only the three silt loam soils as variation of soil characteristics across the three silt loam soils is expected to be minimal. Next the field is assumed to have combinations of all four silt loam and clay soils. In this case, within field soil variation across silt loam and clay soils could lead to a higher return to VRT than fields comprised of silt loam soils only.

Optimal Phosphorus Application Rates for Each Soil.--Equations 1 through 3 were placed in GAMS to determine the optimal (or steady state uniform) phosphorus application

Table 1. Phosphorus Application Rates[1], Associated Yields and Ten-Year Discounted Net Present Value[2].

Crop	Rice		Soybeans		Rotation
Soil	Applied Phosphorus (kg ha^{-1})	Average Annual Yield (kg ha^{-1})	Applied Phosphorus (kg ha^{-1})	Average Annual Yield (kg ha^{-1})	10 Year *NPV* (\$ ha^{-1})
Calloway	52.7	6,759	40.3	2,354	3,511
Calhoun	67.2	6,658	40.3	2,354	3,341
Crowley	50.4	6,204	37.0	2,555	2,921
Sharkey	2.2	6,103	10.1	2,018	2,192

[1]These are the phosphorus application rates for rice and soybeans that maximized discounted net present value of production on each soil.

[2]Discounted Net Present Value (*NPV*) is calculated by adding discounted net revenue values across the ten-year planning horizon. Discounted net revenues are calculated by subtracting costs from revenues in each of the ten years and discounting each year's net revenue by the appropriate discount factor; these are cumulative returns to land, management and risk over the planning horizon. A rice price of \$0.189 kg^{-1}, a soybean price of \$0.239 kg^{-1}, a phosphorus price of \$0.55 kg^{-1}, VRT costs of \$9.88 ha^{-1} and a discount rate of 8.0 percent per annum were used.

rate that would maximize NPV on each soil series. Table 1 presents the resulting phosphorus rates, yields and dollar amounts that maximized NPV on each soil. As expected for silt loam soils, the optimal phosphorus rate on Calloway and Crowley soils were similar. Unexpectedly, optimal phosphorus rates for rice were much higher on Calhoun soils. This may be an EPIC modeling issue but is still considered within normal ranges (Norman, 2000). Phosphorus rates on the Sharkey soils for rice and soybeans were 2.2 and 10.1 kg ha^{-1}, respectively. Although phosphorus rates of zero were expected, this too is within a normal range (Norman, 2000). As expected, the yields on the silt loam soils are higher than those on the Sharkey clay soil.

Surprisingly, optimal phosphorus application rates were insensitive to price or discount rate changes. NPV varied with price ratios but values were consistently positive or consistently negative across the different price and discount rates used. Only magnitudes differed. Likely the variability in prices was too narrow over the five year period studied (1995-1999) to materially affect results. Therefore, only results using 1999 values are reported. A rice price of \$0.189 kg^{-1}, a soybean price of \$0.239 kg^{-1}, a phosphorus price of \$0.55 kg^{-1}, VRT costs of \$9.88 ha^{-1} (AASS, 1999; Randlemann, R. Personal communication) and a discount rate of 8.0 percent per annum were used.

Impacts of Alternative Phosphorus Rates on Yields and Returns on the Four Soils.--Once these optimal uniform application rates were determined for each soil, simulations using equations 4 through 6 were run with alternative (that is rates not optimal for a given soil) phosphorus application rates to estimate yields using uniform rates to capture the effect of sub-optimal application rates across soils. This analysis was conducted to determine what happens to yields and NPV if sub-optimal phosphorus rates are used on each of the four soils. This situation could occur when one phosphorus application rate (say the rate for the Calloway soil) is used across a field that is comprised of multiple soils (a field of Calloway, Calhoun and Sharkey, for example).

Three different uniform rates, abbreviated as *U1*, *U2*, and *U3*, were developed on the basis of the optimal uniform rates that maximized NPV shown in Table 1. *U1* was calculated by taking the average optimal phosphorus rates for Calloway and Crowley silt loam soils. This new U1 rate (that is, 51.6 kg ha^{-1} on rice and 38.7 kg ha^{-1} on soybeans) is appropriate for a field with either Calloway or Crowley silt loam soils. *U2* and *U3* represent the appropriate uniform phosphorus rates for fields with a Calhoun silt loam soil and a Sharkey clay soil, respectively. These rates are the same optimal application rates shown in Table 1 for Calhoun (67.2 kg ha^{-1} on rice and 40.3 kg ha^{-1} on soybeans) and Sharkey clay (2.2 kg ha^{-1} on rice and 10.1 kg ha^{-1} on soybeans) soils.

Table 2 shows the yield and economic losses that occur when *U1*, *U2* and *U3* are misused on each of the four soils. Silt loam soils yields and NPV were most negatively impacted when *U3* was utilized because applied phosphorus was too low. For example, *NPV* fell from \$3,506 ha^{-1} to \$918 ha^{-1} when phosphorus application rates were changed from *U1* to *U3* on the Calloway soil. Similarly, compared to the optimal phosphorus rate application, yields and NPV on the Sharkey clay fell dramatically under *U1* and *U2* rate applications because phosphorus applications were too high.

Table 2. Estimates of Yield and Net Present Value[1] (*NPV*) Losses Under Non-Optimal Phosphorus Application Rates.

Soil	Phosphorus Application Rates[2] *U1*			*U2*			*U3*		
	Yield (kg ha^{-1})			Yield (kg ha^{-1})			Yield (kg ha^{-1})		
	Rice	Soybeans	NPV (\$ ha^{-1})	Rice	Soybeans	NPV (\$ ha^{-1})	Rice	Soybeans	NPV (\$ ha^{-1})
Calloway	N/A[3]	N/A	N/A	6,406	2,286	3,398	4,741	1,950	918
Calhoun	6,456	2,219	3,115	N/A	N/A	N/A	,287	1,345	211
Crowley	N/A	N/A	N/A	5,901	2,286	2,748	4,438	2,017	764
Sharkey	2,875	672	-839	2,471	605	-1,230	N/A	N/A	N/A

[1]*NPV* calculations are as defined in Table 1.
[2]*U1* represents an average rate appropriate for Calloway or Crowley silt loam soils (51.6 kg ha^{-1} on rice and 38.7 kg ha^{-1} on soybeans). *U2* and *U3* represent the appropriate rates for Calhoun silt loam (67.2 kg ha^{-1} on rice and 40.3 kg ha^{-1} on soybeans) and Sharkey clay (2.2 kg ha^{-1} on rice and 10.1 kg ha^{-1} on soybeans) soils, respectively.
[3]N/A indicates that the (appropriate) uniform phosphorus application rate is applied in that case (for example, U1 is the rate appropriate for the Calloway soil) and, therefore, no losses result. Yield and NPV values are the same as those presented in Table 1.

Table 3. Returns to Variable Rate Technology (VRT) on Fields of Silt Loam Soils[1]

Scenario	Field Combination (percent) Calloway	Crowley	Calhoun	$NPV_{VRT} - NPV_{U1}$[2] ($ ha^{-1})	$NPV_{VRT} - NPV_{U2}$ ($ ha^{-1})
1	60	20	20	-13	N/A[3]
2	40	40	20	-9	N/A
3	20	60	20	-5	N/A
4	50	25	25	2	N/A
5	25	50	25	3	N/A
6	60	0	40	27	N/A
7	40	20	40	31	N/A
8	20	40	40	35	N/A
9	50	0	50	49	1
10	25	25	50	54	5
11	0	50	50	59	21
12	20	20	60	N/A	3
13	0	40	60	N/A	5
14	10	20	70	N/A	-20
15	5	25	70	N/A	-17
16	20	0	80	N/A	-44
17	0	20	0	N/A	-32

[1]Silt loam soils are Calloway, Calhoun and Crowley series in this example.
[2]*NPV* calculations are defined in Table 1. Uniform rate applications are described in Table 2.
[3]N/A is not applicable because these *NPV* would result only from uniform phosphorus rate applications that a farmer would not normally use given the majority of the soil in the field.

Profitability of VRT.--Once the relationships between phosphorus application rates, yields, and NPV were established for the four soils individually, the effects of URT and VRT phosphorus applications on fields comprised of more than one soil could be tested. A series of 135 hypothetical one-hectare fields was created. Each of these fields was comprised of various amounts of two, three, and all four soils (see authors for details on soil combinations in the fields). Comparisons of NPV from using VRT (the appropriate application rate for each soil in the field) versus using a uniform phosphorus rate (the rate appropriate for the soil that represented the largest proportion in the field) were then made for each hypothetical field.

Results were first analyzed on fields with different combinations of silt loam soils only. As these soils have similar characteristics, large returns to VRT were not expected. While Table 3 does not provide a complete listing of the returns to VRT for all possible silt loam field combinations, it does highlight the general results. On fields comprised of combinations of the three silt loam soils, results showed that VRT provided greater returns than using one uniform rate (URT) under two conditions. First, VRT was superior to *U1* when Calloway and/or Crowley soils made up between approximately 50 and 75 percent of the field. As more and more Calloway and/or Crowley were present in the field, the difference between VRT and *U1* narrowed. As shown in scenarios one through eleven, Crowley soil has a lessened sensitivity to the average uniform phosphorus application rate *U1*. So that when a field is comprised of 25 to 50 percent Calhoun, net returns to VRT will increase as the proportion of Crowley in that field increases. As Crowley and Calloway are similar soils, these results were unexpected. However, as the difference in profitability is small, this raises little concern and does not affect our general conclusions. Once Calloway and Crowley made up more than 76 percent of the field, VRT was no longer more profitable than *U1*. Second, VRT was superior to *U2* when a field consisted of 50 to 60 percent Calhoun. As more Calhoun enters the field, VRT becomes less attractive compared to *U2*. The same condition applies for the makeup of the remaining soils. While these results do show there may be possible returns to VRT on silt loam soils, the 10 year net returns to VRT are small (reaching a maximum at just under $60 ha^{-1}) and the range of soil combinations where these benefits may be found are limited.

Table 4. Profitability of Variable Rate Technology (VRT) on Fields of All Soils[1]

Scenario	Field Combination (Percent) Calloway	Crowley	Calhoun	Sharkey	NPV_{VRT} - NPV_{U1}[2] (\$ ha^{-1})	NPV_{VRT} - NPV_{U2} (\$ ha^{-1})	NPV_{VRT} - NPV_{U3} (\$ ha^{-1})
1	99	0	0	1	-31	N/A[3]	N/A
2	0	99	0	1	-11	N/A	N/A
3	0	0	99	1	N/A	-32.12	N/A
4	98	0	0	2	-5	N/A	N/A
5	0	98	0	2	0	N/A	N/A
6	0	0	98	2	N/A	-5.02	N/A
7	97	0	0	3	29	N/A	N/A
8	0	97	0	3	49	N/A	N/A
9	0	0	97	3	N/A	36.30	N/A
10	95	0	0	5	90	N/A	N/A
11	0	95	0	5	109	N/A	N/A
12	0	0	95	5	N/A	104.72	N/A
13	40	20	20	20	418	N/A	N/A
14	20	40	20	20	473	N/A	N/A
15	20	20	40	0	469	472.00	N/A
16	20	20	20	40	749	N/A	1,001
17	5	0	0	95	N/A	N/A	63
18	0	5	0	95	N/A	N/A	42
19	0	0	5	95	N/A	N/A	90
20	1	1	1	97	N/A	N/A	12
21	0	0	3	97	N/A	N/A	28
22	2	0	0	98	N/A	N/A	-14
23	0	2	0	98	N/A	N/A	-23
24	0	0	2	98	N/A	N/A	-4
25	1	0	0	99	N/A	N/A	-40
26	0	1	0	99	N/A	N/A	-45
27	0	0	1	99	N/A	N/A	-35
28	0	0	0	100	N/A	N/A	-66

[1]Soils are Calloway, Calhoun and Crowley silt loam and a Sharkey clay.
[2]*NPV* calculations are defined in Table 1. Uniform rate applications are described in Table 2.
[3]N/A is not applicable because these *NPV* would result only from uniform phosphorus rate applications that a farmer would not normally use given the majority of the soil in the field.

Clay soils introduced a greater degree of phosphorus response variability to the field and therefore suggested a larger range of soil combinations over which VRT might be profitable. In fact, as seen in scenarios 7 through 21 in Table 4, VRT was superior to URT in these mixed fields when the proportion of Sharkey was greater than two percent and less than 98 percent. The full range of positive returns to VRT (not shown in Table 4) were roughly \$1.00 ha^{-1} to \$1,003.00 ha^{-1}. The authors note that in this case the range for which VRT is profitable may be extreme and an artifact of the modeling process. However, it does support the idea that VRT can be profitable where soil characteristics, that are important to rice and soybean production processes, are diverse within a given field. Given the broad differences in nutrient requirements between the clay and silt loam soils, application rates desired for one soil series could have devastating effects on yields and thus *NPV* of other soil series. When the clay rate was applied to silt loam soils, yield decreased more than when other silt loam application rates were applied. However, when a silt loam rate was applied to Sharkey clay, yields decreased dramatically. Thus there was much to be gained by applying the proper phosphorus rate to each portion of the field.

Table 5. Summary of Comparison of Variable Rate Technology (VRT) to Uniform Rate Technology (URT)

Soils in the Field	When VRT is Superior to URT
Calloway and Crowley	Never
Calhoun and all Calloway/Crowley combinations	Superior to U1 when Calloway/Crowley mix is between 50 and 75 percent of field
Calhoun and all Calloway/Crowley combinations	Superior to U2 when Calhoun is between 50 and 60 percent of field
Sharkey and all Calloway/Crowley/Calhoun combinations	Superior to U1, U2, and U3 when amount of Sharkey in the field is between 3 and 97 percent

Conclusions

This paper describes some of the results of a study of the profitability of VRT of phosphorus on a rice and soybeans rotation. Yields were found to be responsive to phosphorus application rates. This suggested that in fields comprised of multiple soils, variable rate applications of phosphorus could improve net returns over returns attributed to uniform rate applications alone. However, VRT was found to produce higher net returns than URT only when sufficient variation existed within a field. Cases of sufficient variation (summarized in Table 5) included situations where 1) Calloway and/or Crowley made up between 50 and 75 percent of the field (VRT provided greater net returns than application of the *U1* rate), 2) Calhoun composed between 50 and 60 percent of the field (VRT provided greater net returns than application of the *U2* rate), and 3) the proportion of Sharkey was between three and 97 percent of the field (VRT provided greater net returns than application of any of the *U1*, *U2*, and *U3* rates alone). In general, returns to VRT were small on silt loam fields, less than \$60 ha^{-1} over a ten-year planning horizon, whereas gains to VRT reached as high as \$1,000 ha^{-1} on fields containing both silt loam and clay soils over the same planning horizon.

While this paper gives some indication of the potential profitability of VRT applications of phosphorus in rice and soybeans rotations, it is still unclear how many farmers are likely to adopt the technology. Ongoing efforts of soil scientists at the University of Arkansas are expected to lead to a better understanding of the soil composition of the cropland in major Arkansas crop production regions. With this information, areas where VRT adoption is most likely to occur could be identified as those meeting the criteria outlined above. Adoption will likely also be a function of farm size as farmers earning relatively small returns to precision farming on a small area are not as likely to adopt the technology as larger operations with similar per hectare returns. Finally, further research on the effect of different rice/soybeans rotations on nutrient carryover may affect the applicability of VRT on an annual basis.

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