SPATIAL UTILIZATION OF PHOSPHORUS: IMPLICATIONS FOR PRECISION AGRICULTURE PRACTICES

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Abstract

A dynamic optimization model is used to derive and evaluate phosphorus fertilizer optimal decision rules for irrigated cotton production in the Southern High Plains of Texas. Results indicate that the optimal phosphorus application decision rules critically depend on initial phosphorus availability.

Introduction

Increased use of fertilizer, pesticide, and other chemicals has been an important development in agriculture over the past several decades. Currently, production agriculture is facing significant challenges such as escalating costs of production, shortage of irrigation water, and increased public concern about the impacts of agricultural production on the environment. As world trade liberalization continues, agricultural producers will compete to produce high quality products at low prices for the world market, while attempting to use production practices that are benign to the environment. Traditionally, optimal fertilizer input use in agriculture has assumed spatial and temporal field homogeneity with respect to soil fertility, pest populations, and crop characteristics. That is, optimal fertilizer input decision rules do not account for these differences within fields. Precision farming, precision agriculture or site-specific management recognizes the variability within fields and seeks to optimize variable input use under these conditions. Robert, et al. (1995) state that precision farming for site-specific management is an information and technology based agricultural management system designed to identify, analyze, and manage site-soil spatial and temporal variability with fields for optimum profitability, sustainability, and protection of the environment. In this study, soil fertility in irrigated cotton production stemming from optimal phosphorus fertilizer application is addressed.

The primary objective of this study is to evaluate the economic implications of precision farming practices with respect to phosphorus application in irrigated cotton production in the Southern High Plains of Texas (SHPT). In particular, a dynamic optimization model of phosphorus use that introduces a dynamic phosphorus carry-over function is presented. The SHPT is a semiarid region located in the northwestern part of the state, which encompasses about 22 million acres (35,000 square miles) in 42 counties. Cotton is the most important crop produced in the area in terms of both acreage and crop value. Annual cotton plantings vary between 2.6 and 3.3 million acres in a 25-county region within SHPT, and approximately 50 percent of these acres are irrigated.

The Optimization Model

Contemporary studies (Segarra, Ethridge, Deussen, and Onken; Carter, Jensen, and Bosman; Onken and Sunderman) have found that both fertilizer applications and residual fertility have impacts on crop yields. But most of these studies concentrated on the effects of nitrogen fertilizer and residual on crop yields. This manuscript will address the impacts of phosphorus fertilizer application and residual on cotton yields under different levels of initial soil fertility. That is, a dynamic optimization model is developed to evaluate the relationship between phosphorus application optimal decision rules and residual phosphorus. The model can be expressed as follows. Cotton yield is a function of total phosphorus available to the plants. Total phosphorus available to the plants is equal to applied phosphorus and residual phosphorus at a given time. Phosphorus residual at a given time is a function of the previous phosphorus applications and previous levels of phosphorus residual. Given these relationships, the general form of the optimization model takes the following form:

$$\text{Max } Z = \sum_{t=0}^{n} \{ [P_t \cdot Y_t (PT_t) - CP_t \cdot PA_t] \cdot (1+r)^{-t} \} \qquad (1)$$

Subject to:

$$PT_t = PA_t + PR_t , \qquad (2)$$

$$PR_{t+1} = f_t [PA_t , PR_t] , \qquad (3)$$

$$PR_0 = PR(0) , \qquad (4)$$

and $PA_t , PR_t \geq 0$ for all t.

Where, Z is the per-acre net present value of returns to risk, management, overhead, and all other inputs in the production of cotton ($/acre) in a n period; n is the length of the decision-maker's planning horizon (years); P_t is the price of cotton in year t ($/lb.); Y_t is the cotton yield function in year t (lbs./acre); PT_t is the total phosphorus available to the crop in year t (lbs./acre); CP_t is the price of phosphorus in year t ($/lb.); PA_t is phosphorus applied in year t (lbs./acre); PR_t is phosphorus residual in year t (lbs./acre); and r is the discount rate.

Equation (1) represents the objective function, or performance measure, of the optimization model. Equation (2) is an equality constraint which adds up the applied phosphorus and residual phosphorus at time t, and it is being used in equation (1) to calculate the cotton yield at time t. Equation (3) is the equation of motion which

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updates phosphorus residual. Equation (4) is the initial condition on the level of phosphorus residual at the beginning of the planning horizon.

The field experiments used to derive key relationships in the formulation of this model were conducted at the Agricultural Complex for Advanced Research and Extension Systems (AG-CARES) farm in Lamesa, Texas in 1995, 1996, and 1997. In each year, five phosphorus fertilizer rates (0, 20, 30, 40 and 50) were applied to eight plots -- each with 40 inch rows and 50 feet long. Eighteen replications of the plots were arranged in a randomized block design and located across areas of known variation in cotton yields. All input levels, other than applied phosphorus, were held at the same levels across the replications in the experiment. Cotton yields were calculated by obtaining hand-harvested cotton lint from each plot. Phosphorus residual in the top twelve inches of the soil in each block was measured in each year. Cotton yield functions were calculated with three-year data, and dummy variables were added in order to differentiate factors, such as weather, humidity, and etc., that could not be controlled in the experiment in different years. The phosphorus carry-over function, equation (3), was estimated using the data of 1995 and 1996, and 1996 and 1997.

Using GLM procedures (SAS), several functional forms including logarithmic, Mistscherlich-Spillman, quadratic, and cubic were tried. The functional form found to best fit the data was the cubic form.

$$\begin{array}{l} Y_t = 836.03 + 7.37\ PT_t - 1.35*10^{-1}\ PT_t^2 + 7.47*10^{-3}\ PT_t^3 \\ \qquad (15.32)\quad (2.17)\qquad (-2.13)\qquad\qquad (2.17) \\ + 39.53\ D95\ + 2.90*10^2\ D96 \qquad\qquad\qquad (5) \\ \quad (1.72)\qquad\quad (12.43) \\ R^2 = 0.4229 \end{array}$$

Where, Y_t and PT_t are defined as previously stated; to account for seasonal factors, yearly dummy variables were introduced, specifically D95 and D96. The values in parenthesis below the estimated parameters in each equation are the associated *t*-values. All the estimated parameters in equation (5) were significant at the 0.05 level, except D95, which was significant at the 0.09 level.

Based on the information of phosphorus residual in the soil in 1995, 1996, and 1997, and phosphorus application in 1995 and 1996, the phosphorus carry-over function was estimated to be:

$$\begin{array}{l} PR_{t+1} = 7.74 + 2.33*10^{-1}\ PA_t + 2.23*10^{-1}\ PR_t \qquad (6) \\ \qquad\qquad (3.27)\quad (4.47)\qquad\qquad (2.61) \\ R^2 = 0.1813 \end{array}$$

Where, the variables PR and PA are defined as before and the parameter *t*-values are reported as before. All the estimated parameters in equation (6) were significant at the 0.05 level.

Results

The optimization model depicted in equations (1) through (4) was solved for the condition of 1997 (i.e. D95=D96=0), and all the combinations resulting from: (1) a ten-year planning horizon; (2) five alternative levels of cotton price (0.40, 0.45, 0.50, 0.55, and 0.60 \$/lb.); (3) five alternative levels of phosphorus fertilizer price (0.10, 0.15, 0.20, 0.25, and 0.30 \$/lb.); and (4) three alternative initial conditions of phosphorus in pounds per acre (10, 20, and 30). A 5% discount rate ($r = 0.05$) was used.

As expected, the optimal decision rules for applied phosphorus fertilizer varied across periods in the planning horizon for a given phosphorus and cotton price combination at the different levels of phosphorus residual. However, because a more stable optimal decision rule was desired to simplify management implementation, for a given phosphorus and cotton price combination and initial soil fertility, an additional constraint of equating phosphorus applications across time periods within the planning horizon was introduced.

Solutions to the 75 optimization models (corresponding to three initial phosphorus residual levels, five cotton prices and five phosphorus prices) were obtained using GAMS (General Algebraic Mathematical System) and are presented in Tables 1 through 3. The top portion of each table depicts the optimal levels of phosphorus applications for the alternative cotton-phosphorus price combinations. The bottom portions of the tables depict the associated net per-acre present value of returns.

As depicted in Tables 1 through 3, the optimization models were solved for specific, discrete combinations of phosphorus and cotton prices. However, such strict price combinations are unlikely to exist. Therefore, it was recognized that a generalized relationship based on relative prices of phosphorus-to-cotton rather than absolute prices would be more useful. Consequently, a generalization of the optimal phosphorus application decision rule was derived for each model. The procedure used was to regress the optimal phosphorus application against the phosphorus-to-cotton price ratio. For each given level of initial condition on phosphorus residual, the 25 optimal decision rules of phosphorus application were listed along with their associated phosphorus-to-cotton price ratios; five of these were eliminated since five alternative phosphorus-cotton price combinations for which the optimization model was solved had the same price ratios and thus the same optimal decision rule. The following functional form was then fitted to the remaining 20 points of the optimal decision rules for phosphorus applications and phosphorus-to-cotton price ratios:

$$e^{PA} = A * R^{\beta} * \varepsilon, \qquad (7)$$

Where "e" is the mathematical constant whose natural logarithm is equal to one; R is the phosphorus-to-cotton price ratio; PA is the optimal level of applied phosphorus; A and β are the parameters to be estimated; and ε is the error term. Regression results from the linearized form of equation (7) for the three models were:

$$\begin{array}{llr} \text{(10 lbs./acre)} & PA = 20.18 - \ 2.42 \ln(R) & (8) \\ & \qquad (190.40) \ \ (-24.46) & \\ & R^2 = 0.9692 & \end{array}$$

$$\begin{array}{llr} \text{(20 lbs./acre)} & PA = 19.11 - 2.39 \ln(R) & (9) \\ & \qquad (182.24) \ \ (-24.40) & \\ & R^2 = 0.9691 & \end{array}$$

$$\begin{array}{llr} \text{(30 lbs./acre)} & PA = 18.34 - 2.41 \ln(R) & (10) \\ & \qquad (174.10) \ \ (-24.46) & \\ & R^2 = 0.9692 & \end{array}$$

Where the variables are defined as above and the values in parenthesis below the estimated parameters represent their associated *t*-values. All parameter estimates were significant at the 0.01 level. It is important to stress the fact that equations (8) through (10) were estimated to find an approximation of the continuous form of the phosphorus fertilizer optimal decision rules rather than to test their significance.

Equations (8) through (10) are presented graphically in Figure 1. As shown in this figure, when phosphorus-to-cotton price ratio is between 0.01 to 1.00, the optimal level of applied phosphorus fertilizer in pounds on a per acre bases ranges from 31.33 to 20.18 for initial phosphorus residual level at 10 lbs. per acre; from 30.13 to 19.11 for initial phosphorus residual level at 20 lbs. per acre; from 29.43 to 18.34 for initial phosphorus residual level at 30 lbs. per acre. The information contained in Figure 1 could also be presented to farmers in table form. As expected, given the initial condition on phosphorus residual, the higher the phosphorus-to-cotton price ratio, the lower the optimal level of applied phosphorus fertilizer. Also, given the initial condition on phosphorus residual, the lower the phosphorus-to-cotton price ratio, the higher the optimal level of applied phosphorus fertilizer.

When comparing the results of three different initial levels of phosphorus residual, it can be seen that the higher the initial phosphorus residual, the lower the optimal level of applied phosphorus fertilizer; and that the lower the initial phosphorus residual, the higher the optimal level of applied phosphorus fertilizer. The differences of applied phosphorus fertilizer among three different initial levels are smaller when the phosphorus-to-cotton price ratio is small. These differences increase as the price ratio increases.

Comparing this study to those studies addressing nitrogen fertilizer application and residual effects on crop yields (Segarra, Ethridge, Deussen, and Onken), it can be found that given the initial conditions on phosphorus and nitrogen residual, the differences among different groups for phosphorus are much smaller than the differences among different groups for nitrogen. This might be explained by the fact that phosphorus tends to be much more stable in the soil than nitrogen.

Conclusion and Discussion

The objective of this study was to evaluate the economic implications of precision farming practices, i.e., to derive phosphorus fertilizer application optimal decision rules under different soil fertility scenarios, which consider the dynamic phosphorus residual impacts of phosphorus application in irrigated cotton production. It was shown that given different soil fertility levels with respect to phosphorus, there exist differences on the optimal decision rule of phosphorus application.

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Table 1. Per Acre Dynamic Optimal Levels of Applied Phosphorus and Associated Net Present Value of Returns for Alternative Cotton-Phosphorus Prices, Assuming 10 lbs./acre Initial Condition on Phosphorus

Phosphorus	Cotton Price ($/lb.)				
Price ($/lb.)	*0.40*	*0.45*	*0.50*	*0.55*	*0.60*
			Phosphorus Applied (lbs./acre/year)		
0.30	20.436	20.925	21.325	21.659	21.942
0.25	21.174	21.596	21.942	22.230	22.473
0.20	21.942	22.294	22.592	22.820	23.022
0.15	22.745	23.022	23.246	23.432	23.589
0.10	23.589	23.782	23.939	24.068	24.176
			Net Present Value of Returns ($/acre, 10-year planning horizon)		
0.30	2921.08	3292.21	3663.45	4034.77	4406.16
0.25	2929.12	3300.41	3671.80	4043.24	4414.73
0.20	2937.44	3308.89	3680.39	4051.94	4423.51
0.15	2946.06	3317.63	3689.24	4060.86	4432.51
0.10	2955.01	3326.67	3698.34	4070.03	4441.73

Table 2. Per Acre Dynamic Optimal Levels of Applied Phosphorus and Associated Net Present Value of Returns for Alternative Cotton-Phosphorus Prices, Assuming 20 lbs./acre Initial Condition on Phosphorus

Phosphorus	Cotton Price ($/lb.)				
Price ($/lb.)	*0.40*	*0.45*	*0.50*	*0.55*	*0.60*
			Phosphorus Applied (lbs./acre/year)		
0.30	19.366	19.850	20.246	20.576	20.856
0.25	20.096	20.515	20.856	21.140	21.381
0.20	20.856	21.204	21.488	21.723	21.922
0.15	21.649	21.922	22.144	22.327	22.481
0.10	22.481	22.672	22.826	22.953	23.060
			Net Present Value of Returns ($/acre, 10-year planning horizon)		
0.30	2924.38	3295.60	3666.94	4038.36	4409.85
0.25	2932.00	3303.39	3674.87	4046.42	4418.00
0.20	2939.90	3311.45	3683.05	4054.69	4426.36
0.15	2948.10	3319.77	3691.47	4063.19	4434.93
0.10	2956.62	3328.38	3700.15	4071.93	4443.72

Table 3. Per Acre Dynamic Optimal Levels of Applied Phosphorus and Associated Net Present Value of Returns for Alternative Cotton-Phosphorus Prices, Assuming 30 lbs./acre Initial Condition on Phosphorus

Phosphorus	Cotton Price ($/lb.)				
Price ($/lb.)	*0.40*	*0.45*	*0.50*	*0.55*	*0.60*
			Phosphorus Applied (lbs./acre/year)		
0.30	18.595	19.081	19.479	19.812	20.093
0.25	19.329	19.750	20.093	20.379	20.622
0.20	20.093	20.444	20.729	20.966	21.166
0.15	20.892	21.166	21.389	21.574	21.730
0.10	21.730	21.922	22.077	22.205	22.313
			Net Present Value of Returns ($/acre, 10-year planning horizon)		
0.30	2924.37	3295.37	3666.49	4037.69	4408.95
0.25	2931.69	3302.87	3674.12	4045.44	4416.81
0.20	2939.30	3310.62	3682.00	4053.42	4424.88
0.15	2947.21	3318.66	3690.13	4061.64	4433.16
0.10	2955.44	3326.94	3698.52	4070.09	4441.66

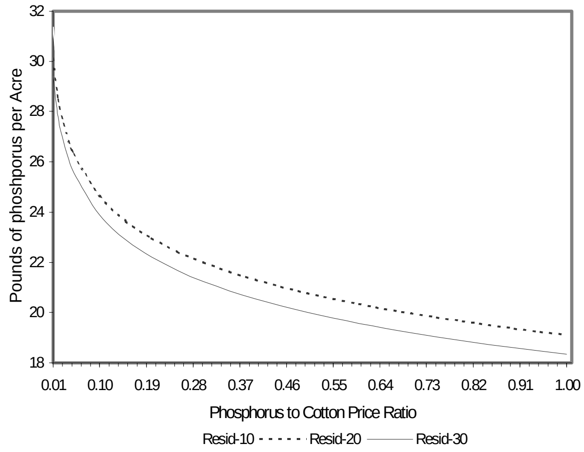

Figure 1. Continuous form of the optimal decision rule of applied phosphorus for different levels of phosphorus residual