INVESTMENT IN SITE SPECIFIC CROP MANAGEMENT UNDER UNCERTAINTY

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1. INTRODUCTION

Recent technical innovations allow farmers to obtain spatially referenced data on nutrient content and soil quality of fields for site-specific crop management (SSCM). By targeting input applications more precisely within a field, SSCM has the potential to improve input utilization, increase input productivity, and raise crop yields. SSCM is a technological package that consists of several components such as satellite-based global positioning systems, grid soil sampling, variable rate fertilizer spreaders, and yield monitors. Despite the potential economic benefits of SSCM, the adoption rates among farmers are still low. For example, only 4% of farmers at the national level adopted variable rate technology and only 6% adopted yield monitors (Daberkow and McBride, 1998); the corresponding figures for the Midwest were 12% and 10% (Khanna et al., 1998).

Most studies on SSCM analyze the economic feasibility of variable rate input application by relying on standard cost-benefit methods (survey in Swinton and Lowenberger-DeBoer, 1998; Babcock and Pautsch, 1998; Weiss, 1998; Thrikawala et al, 1999). Assuming implicitly that either future costs or benefits are certain, these studies focus on whether the potential increase in the discounted net returns is sufficient to cover the investment costs of adopting SSCM. This dichotomous choice, to invest now or never, is not realistic in the presence of output price uncertainty and irreversibility of investment decision since farmers have the flexibility to choose to either invest now or at a later date.

This research, therefore, emphasizes the importance of sunk investment costs, uncertainty in returns, and flexibility in investment timing on farmers' adoption decision as in McDonald and Seigel (1986), and Dixit and Pyndick (1994). Allowing for the presence of these characteristics in investment decisions alters the traditional net present value rule by including the "option value" of delay as a cost. Given uncertainty about output prices and expectations of declining fixed costs of equipment, there may be a value to waiting before investing in it. Applications of this framework to analyze the timing of adoption of agricultural technologies are few (Purvis et al.,1995; Winter-Nelson and Amegbetto, 1998)

The purpose of this paper is to develop a framework that analyzes the determinants of farmers' adoption decision in SSCM under uncertainty and irreversibility. The study analyzes the impacts of heterogeneity within the field as well as economic variables on the optimal timing of adoption by applying an option-pricing model. It examines two alternative approaches to adoption, the owner purchase of all the necessary equipment and the custom hiring, and provides a rationale for the current low rates of adoption. It shows that average soil fertility and soil quality as well as variations in these characteristics are important determinants of the profitability of SSCM. In the presence of the output price uncertainty and irreversibility of the investment, farmers prefer to delay the investment 3 to 25 years unless the average soil fertility and soil quality and their variations within the field are substantially high. The paper is organized as follows: section 2 presents the behavioral model identifying the technology adoption decision under the net present value rule and option value approach. Section 3 describes the empirical analysis while section 4 summarizes the main findings. The last section concludes the paper.

2. THEORETICAL MODEL

2.1. Conceptual Framework

We consider a profit-maximizing farmer operating a field of A acres in which soil fertility levels vary. The crop response function, $y_i = f(x_i, z_i)$, represents the yield in each sub-field $i = 1,2,\ldots,M$ as a function of soil fertility level z and applied input x with $f_x > 0$, $f_z > 0$, and

$f_{xx} < 0$. The soil fertility levels depend on the nutrient content of soils. The average soil fertility within the field is $\bar{z}$ and its variance is s_z^2. The farmer has a discret e choice between two technologies, conventional production practices and SSCM, denoted by C and S, respectively. Dynamic aspects of fertilizer application are incorporated into the model using the relationship between applied input and soil fertility level as $z_{i,t} = z_{i,t-1} + f_1 x_{i,t} - f_2 y_{i,t}$. It is assumed that an increase in applied input increases soil fertility level by f_1 while an increase in harvested crop decreases soil fertility level by f_2 within the field.

The farmer chooses optimal level of $x_{i,t}$ for each $z_{i,t}$ at each instant t using the information available at that time. Under conventional production practices, the farmer determines the average level of soil fertility in the field $\bar{z}_t$ and then chooses the optimal level of input application, x_t^C such that $P_t f_x(x_t^C, \bar{z}_t) = w$. Under SSCM the farmer determines the optimal input levels in each subsection of the field, $x_{i,t}^S$ that solves $P_t f_x(x_{i,t}^S, z_{i,t}) = w$ for all i. It is possible to have corner solutions, i.e., $x_{i,t}^S = 0$ when $z_{i,t}$ is relatively high while in some parts of the field $x_{i,t}^S$ could exceed x_t^C, implying $(x_t^C - x_{i,t}^S) \geq 0$. The output price ($P_t$) is uncertain and the farmer has expectations of these prices in the future. Input price (w) is assumed to be fixed over time. We define the expected quasi-rent differential at time 0 over the lifetime of investment by taking the difference between SSCM and the uniform rate application profits as

$$V_0 = \int_0^{\bar{T}} e^{-tr} E\left[\sum_{i=1}^{M} \left[P_t \left(f(x_{i,t}^S, z_{i,t}) - f(x_t^C, z_{i,t}) \right) - w\left(x_{i,t}^S - x_t^C \right) \right] \right] dt \qquad (1)$$

where E denotes the expectation operator based on the information available at time 0; $\bar{T}$ is the lifetime of the investment; and r is the discount rate.

The first term inside the summation in the equation (1) represents yield gain while the second term indicates the magnitude of cost saving from adoption of SSCM. At t=0, the impact of adoption on yield is approximated as $f_x(x^C - x_i^S) + f_{xx}(x^C - x_i^S)^2$. The first term could be positive or negative depending on whether the plot has above average or below average fertility while the last term is always negative since $f_{xx} < 0$. This indicates that on plots with $x^C < x_i^S$ yields are higher under SSCM than under the conventional practices. On plots with $x^C > x_i^S$ yields are higher (lower) under SSCM than under conventional practices if the second term (first term) on the right hand side is larger than the first ter m (second term). The greater the variability in the soil fertility distribution within the field, the greater is the magnitude of the second term and the greater the potential for yield gains with adoption even if input application is reduced.

The impact of adoption on the aggregate gains in the quasi -rent at t=0 is approximated using a Taylor series expansion to obtain

$$V_0 = -\sum_{i=1}^{M} P f_{xx}(x^C - x_i^S)^2 > 0. \tag{2}$$

Note that equation (2) is positive and indicates that the greater the variability in the soil fertility distribution, the greater the magnitude of quasi -rent differentials. The higher the average fertility level, the higher f_{xx} and $(x^C - x_i^S)$, and therefore the higher V_0. Fields with higher soil fertility on average and greater variability in soil fertility are likely to have higher discounted quasi -rents from SSCM. Thus, gains due to adoption vary with the distribution of soil char acteristics within the field and with the price of output.

2.2. Optimal Investment Rule

Under certainty, the farmer's choice between adopting SSCM and the conventional production practices would be based on a comparison of the costs of investment (I) and the present value of the differential in quasi -rents, V_0. This conventional net present value rule (NPV) implies that the farmer would adopt SSCM at $T=0$ if $V_o{}^{3}\ I$ or the rate of return is greater than r. This rule does not allow price uncertainty to influence adoption decision directly. It does not also take into account the flexibility in timing of adoption, declining trend in the investment cost over time, and irreversibility of investment. Since SSCM technologies are still in their inf ancy, the resulting technological obsolescence of equipment makes it unlikely for farmers to recover their sunk costs if the investment were to be liquidated due to a downward turn in revenues. Hence, the farmer's problem is to choose a time *T to* invest in the fixed capital I for SSCM to maximize

$$F(V) = E\left[V_T e^{-rT} - Ie^{-(r+t)T}\right] \tag{3}$$

where t is the percentage rate of decline in the investment cost. In the presence of price uncertainty, the stream of net returns V_T is uncertain. In order to keep our analysis tractable, we assume that V_T evolves as a geometric Brownian motion

$$dV = aVdt + sVdz \tag{4}$$

where dz is the increment of a Wiener process with mean zero and unit variance; a is the drift parameter and s reflects the volatility in the drift parameter. The solution to the maximization problem in (3) subject to (4) found using dynamic programming shows that the optimal time to invest occurs when (Dixit and Pindyck, 1994, pp.140 -142)

$$V_T \geq \frac{b_1}{b_1 - 1} Ie^{-tT}, \quad \text{where} \quad b_1 = \frac{1}{2} - \frac{a}{s^2} + \sqrt{(\frac{a}{s^2} - \frac{1}{2})^2 + 2\frac{r}{s^2}} > 1 \ . \tag{5}$$

This shows that uncertainty and irreversibility require V_T be greater than Ie^{-tT} by a factor of $\frac{b_1}{b_1 - 1}$. This factor is called the hurdle rate which is a positive function of a and s, and a negative function of r. It indicates the level of caution that should be applied to the adoption decision due to the price uncertainty and irreversible nature of the investment in SSCM.

3. EMPIRICAL ANALYSIS

The empirical analysis considers three fertilizer inputs, nitrogen (*N*), phosphorus (*P*), and potassium (*K*) applied to continuous corn production in Illinois on a 500 acres field with 2.5 acres grid cells. Crop yields on the field depend on choice of technology, soil fertility, and soil quality. Soil fertility depends on soil nutrient levels of *P* and *K* in the soil. Soil quality is represented by the potential yield within the field and depends on the characteristics of soils such as organic matter, sand and clay content of soils. Soil nitrate tests have not been found to be successful in accurately measuring and predicting the available nitrogen in Illinois soils (Illinois Agronomy Handbook, 1998). Therefore, this study does not consider the residual nitrogen in the analysis.

The initial distributions of soil test levels for *P* and *K* and the initial distributions of soil quality are characterized by a Beta distribution because it allows for flexibility in characterizing nonsymmetric distributions. Different field conditions are simulated to examine the impact of soil fertility and soil quality distributions on the timing of adoption by changing the parameters of the distribution. Two alternative soil fertility distributions with low and high mean level are considered, each having three alternative coefficients of variation, referred to hereafter as FCV. Similarly, two alternative soil quality distributions are considered with low and high average potential yield. Each of these soil quality distributions is characterized by two alternative coefficients of variation, referred to as QCV. A modified Mitscherlich-Baule yield response function is used to represent the functional relationship between yield and inputs *N*, *P* and *K*. Its calibration for this study is discussed in Khanna, Isik, and Winter-Nelson (1999). The soil fertility carryover relationship for *P* and *K* is calibrated based on recommendations in the Illinois Agronomy Handbook (1998).

We consider two alternative approaches to adoption of site-specific crop management: (1) owner purchase of all the necessary equipment and (2) custom hiring of some services and purchase of the rest. Under both options, farmers purchase a yield-monitoring bundle including a yield monitor with moisture sensors, a GPS receiver, and mapping software for a total cost of $7855 (Ag Leader). They also do grid soil sampling and testing, which costs $6.4 per acre with 2.5 acres grids. Under the owner purchase package, farmers purchase a variable rate controller equipment for $12,345 while under the custom hiring package they hire the services for variab le rate input application for a cost of $5 per acre annually (Illini FS). Farmers' training cost is also included as a cost of investment along with the maintenance and repair cost of equipment under both options. The annualized fixed cost of the owner pur chase package is $5665 while that of the custom hiring package is $5227. It is assumed that the discount rate is 5% and the lifetime of the equipment is 5 years. All equipment costs are assumed to decline by 5% per annum while cost of custom hire services is assumed to decline by 3% per annum. Prices of nitrogen, phosphorus and potassium are assumed to be $0.2/lb, $0.24/lb and $0.13/lb, respectively.

The stochastic nature of the discounted quasi-rent differentials V_T is arising from uncertainty in the output prices. To incorporate price uncertainty as well as to motivate the assumption of the stochastic process that V_T follows, we analyze the long run behavior of output prices. We examined the real corn prices over the 75 -year period between 1924-1998. We carried out the augmented Dickey-Fuller unit root tests for nonstationarity, and failed to reject the random walk hypothesis. Therefore, output price process is modeled as a geometric Brownian motion to forecast future prices. These forecasted prices are used to predict the discounted quasi-rent differential V_T. The discounted quasi-rent differentials are then used to estimate the parameters of the stochastic process given in equation (4).

4. RESULTS

Adoption of SSCM has significant effects on farm's crop yields and fertilizer costs. The impacts of alternative soil fertility and soil quality distributions on the average per acre revenue, costs and quasi-rent differential with the two technologies are summarized in Table 1. Adoption of SSCM leads to an increase in aggregate yields and therefore an increase in revenue for all soil fertility and soil quality distributions considered here, although the extent of these gains varies with the distributions. Revenue gains from adopt ion of SSCM increase as the average soil fertility and its variation within the field increase. On fields with low average soil quality and 25% QCV, the revenue gains from SSCM in low average soil fertility are $3.2 and $10.7 per acre for 30% and 60% FCV, respectively. The corresponding gains for high average fertility field are $5.8 and $23.7 per acre. Increase in average soil quality and its variations increase the farm's revenue. With low average soil fertility and 30% FCV, the revenue gains on soil dist ribution with low average soil quality are $3.2 and $6.7 for 25% and 40% QCV, respectively while the corresponding figures are $3.7 and $6.6 for fields with high average soil quality (Table 1).

The effects of adoption of SSCM on fertilizer costs are also summarized in Table 1. Fertilizer cost savings with adoption of SSCM decrease as average soil fertility and its variation increase. This is because fertilizer application under SSCM increases as FCV increases and it does not decrease as much as under the conventional practices as the average soil fertility increases. For instance, the fertilizer cost savings on the low soil fertility distribution decrease from $3.1 to $1.3 per acre as FCV increases from 30% to 60% for low soil quality field with 25% QCV. On the other hand, the fertilizer costs with the adoption decreases $2.5 per acre for high quality field with 30% FCV while it increases $2.5 per acre on the field with 60% FCV. As average soil quality increases, fertilizer costs under both technologies incre ase since an increase in average soil quality raises the marginal productivity of fertilizer application. Increase in QCV decreases the fertilizer cost savings because the gain in marginal productivity from the improved soil quality diminishes as the avera ge soil quality rises. Although the fertilizer cost savings decrease as the variability of soil fertility within the field increases, the gains in revenue with increased variability more than offset the reduction in the fertilizer cost savings. As a result , the quasi-rent differentials increase $6.3 -$30.2 per acre as the average soil fertility and soil quality, and their variability within the field increase.

We examine the effects of soil conditions on the timing of adoption of SSCM under both the NPV rule and the option value approach. As shown in Table 2, adoption is not profitable according to the NPV rule on soil distributions with the low average soil quality and soil fertility and relatively uniform distributions. An increase in the level or/and vari ability of the soil fertility and soil quality induces investment under the NPV rule. Since the annualized costs of the custom hire package are very close to those of the owner-purchased package, the NPV rule does not indicate a difference in the adoption decision between the two packages in most of the cases.

As indicated by the hurdle rates in Table 2, option value approach requires the discounted quasi-rent differentials to exceed the investment cost by 1.2 -1.9 times. Immediate investment is only worthwhile on soil distributions where the discounted quasi -rent differential is sufficiently larger than the fixed costs of investment. These soil distributions are the high fertility and high quality with medium to high variability in soil conditions. The opti on value approach suggests a difference in the timing of adoption between the two packages. The critical value of the total gain at which it is optimal to invest is much higher in the case of the owner -purchased package where the fixed costs include a larg er sunk cost.

The option value approach indicate that adoption is not likely to occur in the next 25 years on soil distributions with the low average soil fertility and soil quality levels, and relatively uniform distributions (Table 2). For example, this is the case for the field which has low average soil fertility with 30% FCV and high average soil quality with 25% QCV. When FCV increases from 30% to 60%, the NPV rule recommends immediate investment for this field while the option value approach recommends waiting for 3 years with the custom hire package and 15 years with the owner-purchased package. As average soil fertility and soil quality increase, the delay in the timing of adoption decreases but it is still optimal to wait in some cases rather than invest immediately as suggested by the NPV rule.

In some cases the option value approach recommends delayed adoption while the NPV rule does not suggest immediate adoption (Table 2). An example is the case of low soil fertility field with 45% FCV. Unlike the NPV rule, the option value approach incorporates the decline in the fixed costs over time and flexibility in the timing of adoption, thereby considering the profitability of adoption at a later date.

5. CONCLUSION

This paper applies an option-pricing model to analyze the impacts of uncertainty about output prices and expectations of declining fixed costs on the optimal timing of adoption in SSCM. It provides insight into factors that may explain the current low rates of adoption. The results show that average levels and variations in soil fertility and soil quality within the field are important determinants of profitability of SSCM. As the average levels and variations in these characteristics increase, the net benefit of using SSCM increases substantially. By ignoring the impacts of uncertainty and irreversibility on the adoption decision, the NPV rule recommends immediate adoption under most of the soil conditions considered in this study. However, recognition of the option value indicates that it is preferable to delay the investment for 3 to 25 years unless the average soil quality and fertility levels and their variations within the field are substantially high.

Table 1. Revenue and Fertilizer Costs under Alternative Soil Fertility and Soil Quality Distributions

Soil Fertility (Pounds/ Acre)	FCV (%)	Revenue ($)			Fertilizer Costs ($)			Quasi-rent ($)
		Conven-tional	SSCM	Change due to SSCM	Conven-Tional	SSCM	Change due to SSCM	Change due to SSCM
With low soil quality and QCV = 0.25								
LOW	0.30	286.3	289.5	3.2	52.6	49.5	-3.1	6.3
	0.45	280.2	287.2	7.0	52.6	50.2	-2.3	9.3
	0.60	274.2	284.9	10.7	52.6	51.2	-1.3	12.0
HIGH	0.30	295.9	301.8	5.8	39.6	37.2	-2.5	8.3
	0.45	285.4	299.0	13.6	39.6	39.3	-0.3	13.9
	0.60	271.3	294.9	23.7	39.6	42.2	2.5	21.2
With low soil quality and QCV = 0.40								
LOW	0.30	283.2	289.9	6.7	52.6	48.6	-4.0	10.7
	0.45	276.7	287.6	10.9	52.6	49.5	-3.1	14.0
	0.60	270.3	285.3	15.0	52.6	50.5	-2.1	17.1
HIGH	0.30	293.2	302.2	9.0	39.6	37.2	-2.5	11.5
	0.45	282.2	299.4	17.2	39.6	39.1	-0.5	17.7
	0.60	268.1	295.2	27.1	39.6	41.6	2.0	25.1
With high soil quality and QCV = 0.25								
LOW	0.30	369.9	373.6	3.7	62.1	58.8	-3.2	6.9
	0.45	362.9	370.6	7.7	62.1	59.2	-2.8	10.5
	0.60	356.1	367.9	11.7	62.1	59.9	-2.1	13.8
HIGH	0.30	380.9	387.2	6.2	49.1	45.3	-3.9	10.1
	0.45	369.1	383.9	14.8	49.1	46.9	-2.2	17.0
	0.60	352.8	379.0	26.2	49.1	49.5	0.3	25.9
With high soil quality and QCV = 0.40								
LOW	0.30	367.3	373.9	6.6	62.0	57.8	-4.3	10.9
	0.45	359.9	370.9	10.9	62.0	58.3	-3.8	14.7
	0.60	352.9	368.1	15.2	62.0	58.9	-3.1	18.3
HIGH	0.30	378.9	387.7	8.7	49.1	45.2	-3.9	12.6
	0.45	366.4	384.2	17.7	49.1	46.4	-2.7	20.4
	0.60	349.4	379.2	29.7	49.1	48.6	-0.5	30.2

Low soil fertility indicates an average level of Phosphorus=30 lbs/acre and an average level of potassium = 200lbs/acre.
High soil fertility indicates an average level of Phosphorus=50 lbs/acre and an average level of potassium = 280lbs/acre.
Low soil quality indicates an average potential yield of 130 bushels/acre.
High soil quality indicates an average potential yield of 165 bushels/acre.
FCV refers to coefficient of variation in soil fertility distributions.
QCV refers to coefficient of variation in soil quality distributions

Table 2. Timing of Adoption under Alternative Soil Fertility and Soil Quality Distributions

Soil Fertility (Pounds/Acre)	FCV (%)	Timing of Adoption Option Value Approach (Years)		Adoption Decision NPV Rule	Discounted Quasi Rent Differential at t=0 ($)	Hurdle Rate
		Custom Hire	Owner-Purchase			
With low soil quality and QCV = 0.25						
LOW	0.30	*	*	**	13902	1.231
	0.45	17	25	**	20758	1.385
	0.60	3	15	A	26816	1.485
HIGH	0.30	*	*	**	18268	1.389
	0.45	3	17	A	30540	1.616
	0.60	1	2	A	46580	1.870
With low soil quality and QCV = 0.40						
LOW	0.30	3	14	A[a]	24226	1.236
	0.45	1	3	A	32917	1.292
	0.60	1	1	A	40889	1.336
HIGH	0.30	3	25	A[a]	25167	1.451
	0.45	1	2	A	38893	1.618
	0.60	1	1	A	55435	1.801
With high soil quality and QCV = 0.25						
LOW	0.30	*	*	**	15236	1.160
	0.45	3	15	**	23415	1.275
	0.60	1	3	A	30780	1.343
HIGH	0.30	17	25	**	22331	1.523
	0.45	1	3	A	37613	1.648
	0.60	1	1	A	57541	1.809
With high soil quality and QCV = 0.40						
LOW	0.30	3	14	A[a]	23740	1.306
	0.45	1	3	A	31243	1.386
	0.60	1	1	A	38111	1.468
HIGH	0.30	3	15	A	27806	1.528
	0.45	1	1	A	45225	1.625
	0.60	1	1	A	67220	1.748

* indicates that adoption is not profitable in the next 25 years.
** indicates that adoption is not profitable at $T=0$ according to the NPV rule
'A' implies that adoption at $T=0$ is profitable according to the NPV rule
[a] Adoption of custom hire services is profitable but not owner purchase of SSCM equipment.

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