Sequential Investment in Site-Specific Crop Management Under Output Price Uncertainty: Implications for Nitrogen Pollution Control

Murat Isik, Madhu Khanna and Alex Winter-Nelson

May 2000

Submitted for Presentation as a Selected Paper at the Annual Meeting of American Agricultural Economics Association, July 30-August 3, 2000, Tampa, Florida.

The authors are: Graduate Student, Assistant Professor, and Associate Professor respectively, all from the Dept. of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign.

All correspondence should be made to Murat Isik, Dept. of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, 404 Mumford Hall, 1301 W. Gregory Dr., Urbana, IL 61801, Tel:(217)333-2616, e-mail: isik@students.uiuc.edu.

Sequential Investment in Site-Specific Crop Management Under Output Price Uncertainty: Implications for Nitrogen Pollution Control

1. Introduction

Conventional farm management practices apply nitrogen and other fertilizers uniformly across fields. Because the fertility and quality of soil tend to vary within a field, this practice can lead to over-application of chemicals, low rates of nutrient up-take, and high levels of nitrate runoff, in at least some parts of the field. Recent technological advances in site-specific crop management (SSCM) are making it possible for farmers to acquire detailed information about the spatial characteristics of their fields and target fertilizer applications to meet spatially varying needs. This has the potential to improve yields, reduce fertilizer costs and reduce nitrogen residuals in the soil. However, the decision to adopt SSCM is complicated by at least two factors. First, there is the potential to profitably adopt different components of the technology sequentially or jointly as a package. Second, some components require a large sunk cost, which must be made in the face of revenue uncertainty. This paper presents a method to analyze adoption of interrelated components of a technology under output price uncertainty and applies that method to analyze the use of green payments to encourage adoption of SSCM to reduce nitrogen pollution.

SSCM relies on several interrelated technologies which include diagnostic tools such as grid-based soil testing that gathers information about soil conditions and variable rate technology (VRT) that uses computerized fertilizer spreaders linked to Global Positioning Satellite (GPS) systems to apply fertilizer at a variable rate on-the-go in the field to meet location specific needs. Information gathering through soil testing must occur before fertilizer can be applied using VRT and therefore these components need to be adopted sequentially. However, farmers have a choice of either adopting SSCM as a package by adopting VRT immediately after soil testing or adopting it piecemeal by adopting soil testing and delaying or not adopting VRT at all.

Recent surveys of farmers show that the current rates of adoption of SSCM as a package are low and that farmers appear to be adopting the technology piecemeal or stepwise (see Khanna et al., 1999a). For example, 37% of the surveyed farmers in the Midwest had adopted soil testing but only 12% had adopted VRT for fertilizer application. Uncertainties about the returns of SSCM and its high costs of adoption ranked as two important reasons for non-adoption by a majority of the farmers.

Uncertainties about the returns from adoption could arise for several reasons, such as uncertainty about output prices, yields, and weather. Output price uncertainty is likely to increase in the future with the dismantling of government supply controls and price stabilizing programs by the FAIR Act of 1996 (Ray et al.). As evidence of this, corn prices rose to a ten-year high in 1996 and fell by 40% to a five-year low in 1998. While returns from SSCM are uncertain, investment in some components involves high sunk costs. Since SSCM is still in its infancy and undergoing rapid improvement, the resulting technological obsolescence of existing equipment makes it unlikely for farmers to recover their sunk costs if the investment was to be liquidated due to a downward turn in revenues.

Many studies have analyzed the economic and environmental impacts of adoption of soil testing (Schnitkey et al.; Babcock et al.) or SSCM as a technology package (Thrikawala et al.; Schnitkey et al.; Watkins et al.; Babcock and Pautsch). These studies treat adoption as a one-time decision and rely on the traditional net present value (NPV) method in their analysis, assuming implicitly that future returns and costs are certain or that the investment is reversible. In the case of SSCM sequential adoption is attractive because the gains from adoption of VRT depend on the extent of spatial variability in soil conditions, which can only be determined after farmers undertake soil testing. A few studies (Feder; Leathers and Smale) show that differences in fixed costs, risk aversion or the need for learning about a technology can lead farmers to adopt certain components of a technological package before others. However, these studies do not examine the optimal timing of adoption of interrelated components under uncertainty. This paper extends work on sequential adoption by introducing uncertainty using the option value approach of Dixit and Pindyck and by applying the model of sequential investment under uncertainty to SSCM.

While a growing body of work uses the option value approach to explain the timing of adoption of agricultural technologies (Purvis et al.; Winter-Nelson and Amegbetto; Price and Wetzstein; Khanna et al., 1999b), these papers analyze adoption of an indivisible technology. Bar-Ilan and Strange analyze the optimal timing of sequential investment in a two-stage project, but their model does not allow for simultaneous adoption of all components or for returns from the adoption of individual components, both of which are possible with SSCM.

This paper has three purposes. First, it adapts the Dixit and Pindyck option value approach to examine the extent to which output price uncertainty and high sunk costs interact to create incentives to delay adoption of site-specific technologies and to adopt them piecemeal rather than as a package[1]. It also undertakes an assessment of the impacts of heterogeneity in soil conditions on the optimal timing of adoption of each of the components. Second, the paper assesses the extent to which the NPV rule provides misleading predictions of adoption rates by ignoring uncertainty and the option to delay investment and assesses the degree to which ignoring piecemeal adoption within the option value approach misrepresents the returns to SSCM.

[1] While the services of some of the equipment for SSCM can be custom-hired, several components such as yield monitors need to be owner-purchased, while others such as soil testing and mapping involve one time sunk costs. While custom-hiring of some of the services of VRT could reduce the sunk costs of adoption, they are still significantly high.

Third, the paper examines the implications of output price uncertainty and high sunk costs on the design of cost-share subsidies to achieve pollution reduction by accelerating adoption. Various federal farm programs such as Environmental Quality Incentives Program seek to encourage farmers to adopt improved nutrient management practices by offering them green payments. This paper analyzes the optimal targeting of these subsidies across heterogeneous soil conditions as well as how these subsidies should differ in their incentives for adoption of soil testing and VRT. The framework developed here is applied to timing and implications of adoption of SSCM for corn production using production and pollution relationships calibrated to soil conditions in Illinois.

The paper shows that recognition of the possibility of investing in soil testing and VRT sequentially lowers the threshold value of required net returns to invest in soil testing. Since the sunk cost of adopting soil testing is smaller than that of investing in VRT, the possibility of delaying or never adopting VRT makes farmers more willing to invest in soil testing to explore the benefits of SSCM, than to adopt the complete technology in one step. The NPV rule over-predicts adoption of both soil testing and VRT. The analysis also shows that adoption of both soil testing and VRT reduces nitrogen pollution with a large part of this reduction achieved by simply adopting soil testing. Recognizing the option value of investment but ignoring the potential for stepwise adoption would tend to under-predict the adoption of soil testing and over-predict the adoption of VRT. It would also lead to an underestimation of the required subsidy for inducing immediate adoption of VRT and overestimation of that required for soil testing. Cost-share subsidies to accelerate the adoption of VRT would be most effective at reducing nitrogen pollution if targeted towards fields with low average soil quality and high spatial variability in soil fertility or soil quality. The next section presents the theoretical framework to analyze sequential investment decisions. Section 3 describes the data used in the numerical simulation.

The results of the simulation are in Section 4 followed by the conclusions.

2. Theoretical Model

We consider a profit-maximizing farmer operating a field of *A* acres. Soil fertility levels vary within the field and the distribution of soil fertility is represented by a probability density function, $g(z)$ with mean μ and variance σ^2. The level of soil fertility ranges from a lower bound *l* to an upper bound *u.* Assuming a constant returns to scale crop response function, the yield per acre (*y*) at any time (*t*) is described as[2]: $y_t = f(z_t, x_t)$, where *z* represents the soil fertility level per acre and *x* is the applied input per acre. We assume that $f_z>0$, $f_x>0$, $f_{zz}<0$, and $f_{xx}<0$. The farmer has a discrete choice between three alternatives: (a) using the conventional application practices, (b) adopting soil testing only, or (c) adopting both soil testing and VRT. These choices are denoted by superscripts *C*, *S,* and *B,* respectively. The farmer is assumed to be a price-taker in the input and output market. Output price P_t is assumed to be changing over time and the farmer has expectations of these prices in the future. Input price *w* is assumed to be constant. The total fixed cost of adoption of both soil testing and VRT is denoted by $K_t^B = K_t^V + K_t^S$, where the superscript *V* denotes VRT. These costs are assumed to decline over time at the rates δ^S and δ^V respectively, which implies that $K_t^S = K_0^S e^{-\delta^S t}$ and $K_t^V = K_0^V e^{-\delta^V t}$. The lifetime of the equipment for variable rate application is $\overline{T}$ years and the discount rate is ρ.

In order to examine the environmental implications of SSCM, we assume that a part of the applied input is absorbed by the crop and converted into dry grain matter, θy_t (as in Barry et al.; Thrikawala et al.). The rest of the applied input may be carried over in the soil and change

---

[2] Since we are assuming that time is a continuous variable, the time dependent variables should be denoted as *X(t)*. However, for the ease of exposition we are denoting them as X_t.

the level of soil fertility by $\dot{z}$ per acre and/or generate polluting run-off (R_t) per acre:

$$R_t = x_t - \theta\, y_t - \dot{z}\,. \tag{1}$$

Decision Problem under Certainty

The optimal adoption decision under certainty requires that the farmer adopt a technology if the difference in the present value of the quasi-rents (revenue minus variable costs) with and without adoption is greater than the additional fixed costs of adoption. This decision making process involves forecasting the optimal stream of expected returns with the conventional application practices, with soil testing alone, and with both soil testing and VRT, and comparing them to each other and the fixed costs of adoption.

Under the conventional application practices, the farmer lacks information about the distribution of soil fertility in the field but uses a small sample of soil tests to estimate the average soil fertility μ in the field. The farmer then chooses the optimal level of input use per acre for the whole field by maximizing the discounted value of expected quasi-rents, π_0^C, as follows:

$$\pi_0^C = \max_{x_t} \int_0^{\bar{T}} e^{-\rho t} A\big(E(P_t) f(x_t, \mu_t) - w x_t\big) dt\,. \tag{2}$$

Optimal input use per acre is determined such that

$$\frac{\partial \pi_0^C}{\partial x_t} = E(P_t) f_x(x_t, \mu_t) - w = 0\,. \tag{3}$$

where E denotes the expectations operator based on the subjective probability distribution of future prices given the information available at time $t=0$. The optimal amount of input use per acre is obtained as $x_t^C = x(E(P_t), w, \mu_t)$.

Soil testing provides the farmer with information about the distribution of soil fertility $g(z)$ which can be used to choose a single rate of input use for the whole field to maximize the expected value of discounted quasi-rents, π_0^S:

$$\pi_0^S = \max_{x_t} \int_0^{\bar{T}} e^{-\rho t} \left[\int_l^u A\big(E(P_t) f(x_t, z_t) - w x_t\big) g(z) dz \right] dt . \tag{4}$$

The optimal uniform input application per acre is determined such that

$$\frac{\partial \pi_0^S}{\partial x_t} = \int_l^u \big(E(P_t) f_x(x_t, z_t)\big) g(z) dz - w = 0 . \tag{5}$$

Because the optimal input application per acre depends on the distribution of soil fertility, $x_t^S = x(E(P_t), w, g(z))$.

The adoption of both soil testing and VRT makes it possible for the farmer to apply the input at a spatially varying rate across the field. The farmer chooses the optimal level of x_t given the soil fertility z_t to maximize the discounted quasi-rents as:

$$\pi_0^B = \max_{x_t} \int_0^{\bar{T}} e^{-\rho t} \left[\int_l^u A\big(E(P_t) f(x_t, z_t) - w x_t\big) g(z) dz \right] dt \tag{6}$$

$$\frac{\partial \pi_0^B}{\partial x_t} = E(P_t) f_x(x_t, z_t) - w = 0 \quad \forall z . \tag{7}$$

The optimal input level at any point in the field depends on the soil fertility level at that point; thus $x_t^B = x(E(P_t), w, z_t)$.

The optimal input levels with each technology obtained using conditions (3), (5) and (7) are used to find the optimal values of the discounted quasi-rents, π_0^{C*}, π_0^{S*} and π_0^{B*} respectively. The present value of the quasi-rent differential from adopting soil testing only is denoted by $N_0^S\big(P, w, \mu, g(z), \bar{T}, A\big) = \pi_0^{S*} - \pi_0^{C*}$ while that from adopting both components is denoted by

$N_0^B\left(P, w, \mu, g(z), \overline{T}, A\right) = \pi_0^{B*} - \pi_0^{C*}$. We can disaggregate the quasi-rent differential due to adoption of both soil testing and VRT to obtain the quasi-rent differential due to adoption of VRT as: $N_0^V = N_0^B - N_0^S$. The quasi-rent differentials N_0^B and N_0^S are always non-negative since input choice with either soil testing or both components is based on more information and fewer constraints. We would expect these quasi-rent differentials to increase when the variability in the soil fertility distribution increases.

Under the NPV rule, the choice between adopting a site-specific technology and the conventional production practices would be based on a comparison of the costs of investment and the present value of the differential in quasi-rents. It would be optimal to adopt both components of SSCM as a package at *t=0* if $N_0^B > K_0^B$ and $N_0^V > K_0^V$. Adoption of only soil testing would be optimal if $N_0^S > K_0^S$ and $N_0^V < K_0^V$.

Sequential Investment under Uncertainty

Suppose that the quasi-rent differentials, N_T^B, N_T^V and N_T^S, are uncertain due to uncertainty about output prices. In order to keep our analysis tractable, we assume that these quasi-rent differentials evolve as a geometric Brownian motion

$$dN^j = \alpha^j N^j dt + \sigma^j N^j dz^j \qquad j=S, V, B \tag{8}$$

where *dz* is the increment of a Wiener process with mean zero and unit variance; α is the drift parameter; and σ reflects the volatility in the drift parameter.

The decision problem is to determine the optimal time $\hat{T}$ at which to adopt soil testing and the optimal time $\tilde{T}$ at which to adopt VRT where $\tilde{T} \geq \hat{T}$ due to sequential nature of the two decisions. This decision problem is transformed into a two-stage sequential investment in which the first stage involves the decision to adopt soil testing and the second stage involves the decision to adopt VRT. We use backward induction to first solve the second stage investment problem and then use it to solve the first stage problem. In the second stage, we determine $\widetilde{T}$ by maximizing the discounted net returns from adoption of VRT. Net returns are defined as the difference between the quasi-rent differential, N_T^V and the fixed costs of adoption of VRT and are represented by:

$$F^V(N_T^V) = E\left[\left(N_T^V - K_T^V\right)e^{-\rho T}\right]. \tag{9}$$

$F^V(N_{\widetilde{T}}^V)$ may be thought of as the value of the option to invest in VRT. This option value is only available to those who have invested in soil testing. Assuming risk neutrality, (9) is maximized subject to the condition in (8) with *j=V*. The solution to this problem that is found using dynamic programming shows that it is optimal to invest in VRT at $\widetilde{T}$ when the critical value of the quasi-rent differential $N_{\widetilde{T}}^{V*}$ is (Dixit and Pindyck, pp.140-142):

$$N_{\widetilde{T}}^{V*} = \frac{\beta^V}{\beta^V - 1} K_{\widetilde{T}}^V \text{ where } \beta^V = \frac{1}{2} - \frac{\alpha^V}{(\sigma^V)^2} + \sqrt{\left(\frac{\alpha^V}{(\sigma^V)^2} - \frac{1}{2}\right)^2 + \frac{2\rho}{(\sigma^V)^2}} > 1. \tag{10}$$

The investment rule under uncertainty and irreversibility requires N_T^V to be greater than K_T^V by a factor of $\frac{\beta^V}{\beta^V - 1} > 1$. This factor is a positive function of the growth rate and the volatility of the growth rate in N_T^V as indicated by (8), and a negative function of the discount rate. It varies with the characteristics of soil distribution, and indicates the level of caution that should be applied to the adoption decision due to the price uncertainty and irreversible nature of the investment.

Given $F^V(N_{\widetilde{T}}^V)$, the optimal time to invest in soil testing is found by maximizing the net returns from soil testing subject to (8) with *j=S* as:

$$F^S(N_T^S) = E\left[\left(N_T^S - K_T^S\right)e^{-\rho T}\right] + F^V(N_T^V). \tag{11}$$

The solution to the maximization problem in (11) shows that the optimal time $\hat{T}$ to invest in soil testing is when the critical value of the quasi-rent differential due to soil testing is

$$N_{\hat{T}}^{S*} = \frac{\beta^S}{\beta^S - 1}\left(K_{\hat{T}}^S - F_V(N_{\hat{T}}^V)\right). \tag{12}$$

The critical value of the quasi-rent differential required to induce investment in soil testing increases with an increase in $\frac{\beta^S}{\beta^S - 1}$, an increase in the fixed costs of soil testing, and a decrease in the value of the option to invest in VRT. The anticipation of high returns from subsequent adoption of VRT creates incentives for investment in soil testing even when the quasi-rent differential due to soil testing is less than its fixed costs. If the solution to the above two-stage problem shows that $\tilde{T} > \hat{T}$ then the optimal decision is to adopt soil testing at time $\hat{T}$ and to delay the adoption of VRT till $\tilde{T}$. When the optimal time to invest in soil testing and VRT is $\tilde{T} = \hat{T}$, it is optimal to adopt both components at the same time.

A decision rule that ignores the possibility of adopting the components stepwise imposes the constraint that $\tilde{T} = \hat{T}$. This requires the adoption of VRT immediately after the adoption of soil testing. If piecemeal adoption were prohibited or if these two technologies were bundled together as a package, the optimal time T to invest in both soil testing and VRT would be obtained by maximizing the net returns from both soil testing and VRT subject to (8) with $j=B$:

$$F^B(N_T^B) = E\left[\left(N_T^B - K_T^B\right)e^{-\rho T}\right]. \tag{13}$$

The solution to (13) shows that the critical value of the quasi-rent differential at which it is optimal to invest in the SSCM package is:

$$N_T^{B*} = \frac{\beta^B}{\beta^B - 1}K_T^B. \tag{14}$$

A cost-share subsidy may be used to induce adoption when it is not optimal to invest in soil testing and VRT immediately. Under the NPV rule, the required cost-share subsidy for immediate investment is the difference between the present value of quasi-rent differential and the cost of investment when the former is greater than the latter. Under the option value approach, when the possibility of stepwise adoption is recognized, the subsidy required for immediate investment differs for soil testing and VRT. The required cost-share subsidy for soil testing if $N_0^{S*} > N_0^S$ is:

$$H^S = K_0^S - \frac{(\beta^S - 1)}{\beta^S} N_0^S - F^V(N_0^V). \tag{15}$$

The required subsidy for VRT if $N_0^{V*} > N_0^V$ is:

$$H^V = K_0^V - \frac{(\beta^V - 1)}{\beta^V} N_0^V. \tag{16}$$

If SSCM is treated as a package and $N_0^{B*} > N_0^B$, the subsidy required to induce immediate investment in both components is calculated as:

$$H^B = K_0^B - \frac{(\beta^B - 1)}{\beta^B} N_0^B. \tag{17}$$

The subsidy required to induce adoption of site-specific technologies depends on the net present value of quasi-rent differentials N_0^j, the option value of investment and the costs of investment. The quasi-rent differential and the option value, and therefore the subsidy required for immediate adoption as indicated by (15)-(17) vary with the distribution of soil characteristics. The required subsidy under the option value approach is always higher than that under the NPV rule because of the need to compensate for option values for given soil conditions. The total subsidy for immediate investment in both soil testing and VRT as a package H^B could be lower or higher than the total subsidy under the sequential investment rule, $(H^S + H^V)$ depending on the values of $\frac{\beta^j}{\beta^j - 1}$ and $F^V(N_T^V)$. This is an empirical question, and we examine that by developing a simulation model for corn production in Illinois.

3. Empirical Analysis

The empirical analysis considers three fertilizer inputs; nitrogen (X_N), potassium (X_P) and phosphorus (X_K) applied to corn production under Illinois conditions on a 500-acre farm field. These 500 acres are divided into 200 plots with an area of 2.5 acres each. Soil conditions on the farm are characterized by two features – soil fertility and soil quality. Soil fertility is defined in terms of the levels of phosphorus and potassium in the soil. Soil quality depends on characteristics such as organic matter and the sand and clay content of soil. These characteristics determine the productivity of the soil and its maximum potential yield per acre under given climatic conditions. This study does not consider the possibility of measuring residual nitrogen in the soil since soil nitrate tests have not been found to be successful in accurately measuring and predicting the available nitrogen in the soil under Illinois conditions (Illinois Agronomy Handbook). Nitrogen requirements of the crop depend on the quality of the soil as represented by its maximum potential yield.

The level of phosphorus is assumed to range from 10 lbs per acre to 180 lbs per acre while the level of potassium is assumed to range from 120 lbs per acre to 680 lbs per acre (Illinois Agronomy Handbook). Maximum potential yields on Illinois soils vary between 60 bushels per acre and 200 bushels per acre (Olson and Lang). The distributions of soil nutrient levels of phosphorus and potassium and the distribution of soil quality are characterized by appropriately scaled Beta distributions (as in Caswell et al. and Dai et al.). Alternative soil conditions are simulated by changing the means and variances of the Beta distributions. Two alternative mean levels (low and high) of soil fertility are considered with three alternative coefficients of variation of the soil fertility distribution (CVF). Similarly, two alternative soil quality distributions are considered with low and high levels of average potential yield. Each of these distributions is characterized by two alternative coefficients of variation of the soil quality distribution (CVQ).

A modified Mitscherlich-Baule yield response function is used to represent the functional relationship between crop yields and three fertilizer inputs: nitrogen, phosphorous, and potassium (as in Schnitkey et al.). Frank et al. and Dai et al. use experimental data on corn yields to demonstrate the validity of the Mitscherlich-Baule function relative to other more restrictive functional forms such as von Liebeg, quadratic, and cubic. We used data from the Illinois Agronomy Handbook to calibrate the Mitscherlich-Baule production function with inputs nitrogen, potassium, and phosphorous and obtained:

$$y_i = h_i(1-e^{-(0.51+0.025x_{iN})})(1-e^{-(0.28+0.1(x_{iP}+z_{iP}))})(1-e^{-(0.115+0.012(x_{iK}+z_{iK}))}) \quad (18)$$

where h_i represents the maximum potential yield; and Z_{iP} and Z_{iK} represent the amount of phosphorus and potassium (respectively) present in the soil in plot i=1,…,200.

The soil fertility carryover equation (1) for phosphorus and potassium is calibrated based on recommendations in the Illinois Agronomy Handbook. It is assumed that 0.43 lb. of phosphate and 0.28 lb. of potash are removed from the soil per bushel of harvested corn. It is also assumed that 9 lbs. of phosphate increase the nutrient level of phosphorus by 1 lb. per acre while 4 lbs. of potash increase the nutrient level of potassium by 1 lb. per acre. Applied phosphorus and potassium in excess of those absorbed by plants are carried over by the soil and raise soil fertility levels for the next crop[3]. In the case of nitrogen we assume that 0.75 lbs. of

[3] Phosphorus and potassium are not mobile nutrients and usually remain in the soil and contribute to environmental contamination only through soil erosion (Illinois Agronomy Handbook, Schnitkey et al.).

applied nitrogen are absorbed by a bushel of corn and that all excess nitrogen in the soil is potentially available for leaching (Barry et al.).

SSCM is defined here to include soil testing and sampling that is typically done once in four years as well as the adoption of variable rate application technology and yield monitors. We assume that subsequent to the initial soil testing, the farmer tracks the spatial variability in soil conditions in the field by using a yield monitor and uses that to guide the spatially varying input applications with VRT. The cost of grid soil sampling and testing at the 2.5 acre level is $6.4 per acre or $3200 for the 500 acres. The yield-monitoring bundle includes a yield monitor with moisture sensors, a GPS receiver, a field marker, mapping software and memory cards and is sold by Ag Leader for $7855. The variable rate application equipment together with the application software can be purchased for $12,345. Annual costs of maintenance and repair are assumed to be 1% of the equipment cost. Finally, farmers adopting SSCM need to undergo training in the use of equipment, which is a one-time sunk cost at the time of adoption. The total cost of the package of VRT is $22, 243.

All equipment costs are assumed to decline in real terms by 5% per annum while costs of custom hire services and soil testing are assumed to decline by 3% per annum. Discount rate is assumed to be 5% while the lifetime of the equipment is assumed to be 5 years. Prices of nitrogen, phosphorus and potassium are assumed to be at their 1997 levels of $0.2/lb, $0.24/lb and $0.13/lb respectively.

The stochastic nature of the discounted quasi-rent differentials in (8) arises from uncertainty in the output prices. To characterize the price uncertainty and support the assumption that N_T^j evolves as a geometric Brownian motion, we analyze the long run behavior of output prices by examining the historical data on real corn prices over the period 1926-1998 (USDA). We examine whether the output price process is non-stationary or stationary by conducting we estimate Dickey-Fuller unit root test. We fail to reject the null hypothesis that the price process is non-stationary. Hence, the output price process is modeled as a geometric Brownian motion represented by the following discrete approximation (Dixit and Pindyck, pp.72):

$$P_t = (1+\gamma)P_{t-1} + \lambda P_{t-1}\nu_t \tag{19}$$

where γ is the drift parameter; λ is the standard deviation in the drift parameter; and ν_t is a random variable with mean zero and unit variance. The value of γ, estimated as the average percentage changes in real corn prices between 1926-1998, is found to be -0.014. The standard deviation of the average percentage changes is estimated to be 0.223. This process is used to forecast prices for a 25-year period by assuming random shocks drawn from a standard normal distribution. These prices are used to forecast the discounted quasi-rent differential N_T^j. A series of N_T^j is estimated for 25 years under each of the alternative assumptions about the parameters of the soil fertility and soil quality distributions. For each of these series we then estimate α^j and σ^j to characterize the stochastic process followed by N_T^j in (8).

4. Results

Implications of Adoption of Site-Specific Technologies for Quasi-Rent

The impacts of alternative soil fertility and soil quality distributions on the average per acre discounted quasi-rents (revenue minus variable fertilizer costs) over the 5-year lifetime of the equipment with the conventional application practices, soil testing, and both soil testing and VRT are summarized in Table 1. Quasi-rents with all three adoption decisions increase as the average soil fertility within the field increases since that reduces the need to apply as much fertilizer. The quasi-rents also increase with an increase in the average level of soil quality since the increased soil quality increases the marginal productivity of inputs.

The adoption of both soil testing and VRT leads to an increase in quasi-rents, relative to those with the conventional application practices, for all soil fertility and soil quality distributions, as expected from the theoretical analysis above (Table 1). As average soil quality increases, it leads to an increase in the uniform application rate for all inputs under the conventional practices. This increases costs more than it increases yields per acre and thus increases the gains in quasi-rent with adoption of one or both components of SSCM. An increase in the average level of soil fertility, on the other hand, reduces the quasi-rent differential of both soil testing and VRT since the yield gains and fertilizer cost savings with adoption decrease due to diminishing marginal productivity of inputs as soil fertility increases. An increase in the variation of soil quality and/or soil fertility increases the quasi-rent differential with both soil testing and VRT because it increases the proportion of the field constrained, under the conventional practices, to receiving less fertilizer in some parts of the field and more fertilizer in other parts of the field.

Hence, the levels of soil fertility and soil quality in the field work in opposite directions in their effect on the quasi-rent differentials with adoption of soil testing or both components. Increased variability in either, however, has a positive effect on these quasi-rent differentials. High average soil quality, low average soil fertility and high variability in both leads to higher quasi-rent differentials than low, high, and low, respectively. These results are consistent with the findings of other simulation studies that examine the impacts of adoption of soil testing and VRT on alternative soil fertility distributions (Thrikawala et al.) and alternative soil quality distributions (Babcock and Pautsch). While these studies focus on a single soil attribute, this paper shows that it is important to consider a combination of soil attributes when assessing the quasi-rent differential since some of these soil attributes interact in opposing ways.

Additionally, in this study we disaggregate the quasi-rent differential with adoption of both soil testing and VRT into that due to each of the components. The contribution of VRT to the quasi-rent differential is greater than that of soil testing on all the soil distributions, with the exception of those with high average quality and low average fertility (Table 1). As expected, the incremental contribution of VRT to the total quasi-rent differential increases as the variability in soil conditions increases. The gains with the adoption of soil testing range between $3.3 per acre on the soils with high average quality and low average fertility and $25.7 per acre on the soils with low average fertility and high average quality. The incremental contribution of VRT ranges between $7.8 per acre and $29.2 per acre on these soils.

The discounted quasi-rent differentials of both soil testing and VRT exceed the fixed costs of adoption on most of the soil conditions considered here. As shown in the last column of Table1, according to the NPV rule that ignores uncertainty and irreversibility, adoption of both soil testing and VRT is preferred to the conventional application practices on all the soil conditions except on the soils with low average quality, 25% CVQ and 30% CVF. On such soil conditions, adoption of only soil testing is profitable.

Optimal Timing of Adoption

We now examine the impacts of output price uncertainty on the optimal timing of adoption under the alternative assumptions of whether SSCM is adopted as a package or sequentially. The optimal timing of adoption of soil testing and VRT are obtained by calculating the critical values for investment, reflecting both the quasi-rent differentials and the option values associated with adoption. Recognizing the possibility of stepwise adoption, we calculate the critical values of soil testing and VRT using the factor $\beta/(\beta-1)$ given in Table 2. This term $\beta/(\beta-1)$ reflects the degree to which the quasi-rent differential must exceed the investment costs before investment will occur, given uncertainty and sunk costs. The value of this factor varies with the distribution of soil characteristics within the field, indicating the role that soil characteristics play in mitigating the effects of uncertainty on the adoption decision. For soil testing, this factor decreases as the average soil quality and variation in the soil quality increase while it increases with an increase in the average soil fertility and variability in the soil fertility. This occurs because increased average fertility increases the variation in the quasi-rent differential while increased average soil quality reduces the variation. The magnitude of $\beta/(\beta-1)$ for soil testing ranges from 1.4 on the low average fertility and quality soils to 3.4 on the high average fertility and quality soils. The values of $\beta/(\beta-1)$ for VRT are higher than those of soil testing for all the soil distributions except for the high average quality and fertility soils. These values range from 1.7 on the high average fertility to 3.8 on the low average fertility soil (Table 2).

The analysis shows that the possibility of future adoption of VRT encourages immediate adoption of soil testing on all the soil distributions considered here. The reason is that the adoption of soil testing not only provides the benefits of determining the optimal single rate of input application for the field but also keeps alive the option to adopt VRT in the future. The value of the option to adopt VRT lowers the critical value of net returns at which adoption of soil testing is optimal and makes the immediate adoption of soil testing worthwhile. However, it is optimal to delay the adoption of VRT on most of the soil conditions. This is because high option values to VRT (due in part to the technology's high fixed costs) create critical values of net returns at which it is optimal to adopt that are much higher than the quasi-rent differentials. Immediate adoption (at year 1) of both soil testing and VRT is only worthwhile on soil distributions with high average quality, low average fertility and relatively high variability in both. Unlike the NPV rule, this decision rule recommends waiting 2 to 17 years before adopting

VRT on most of the soil distributions considered here[4] (Table 2). It recommends more waiting on the high average fertility and the low average quality soils with low variability in both. As the variability in these characteristic increases, the waiting time decrease substantially.

When the decision rule is constrained to adoption of VRT immediately after the adoption of soil testing, the total discounted quasi-rent differential must be 1.3 to 2.5 times greater than the total costs of investment, as indicated by the factor $\beta/(\beta-1)$ (last column in Table 2). This factor also varies with the distribution of soil characteristics and in most cases lies in between the factor estimated separately for soil testing and for VRT. This implies that considering SSCM as a package underestimates the critical value of the quasi-rent differential at which it is optimal to adopt VRT while it overestimates the critical value of the quasi-rent differential of soil testing. It therefore tends to predict that adoption of VRT is profitable earlier than that predicted by the sequential analysis, particularly on soil distributions with low average quality and fertility (as shown in column 2 of Table 2). Hence, considering SSCM as a package results in poor predictions of optimal timing of adoption of soil testing and VRT.

Implications of Soil Testing and VRT for Pollution Control

The impacts of adoption of soil testing and VRT on nitrogen pollution under alternative soil quality and soil fertility distributions are summarized in Table 3. Average per acre pollution levels with all three technology choices are higher on soil distributions characterized by the low average quality and the low average fertility, indicating that nitrogen uptake by plants on low

[4] Impacts of an increase in discount rate on the timing of adoption are also analyzed. An increase in the discount rate from 5% to 10% has two effects. First, increased discount rate slightly reduces the value of $\beta/(\beta-1)$, which would reduce the critical value at which it is optimal to invest. Second, it also reduces the discounted value of the quasi-rent differential marginally. Its net impact on the timing of adoption was therefore not found to be significant.

average quality soils is lower than on high average quality soils. As the variability in soil fertility and soil quality increases, input applications increase while the crop yields obtained decrease, which results in an increase in nitrogen pollution under all the technologies. However, the increase is much lower with the adoption of soil testing and VRT. Our analysis shows that adoption of soil testing and VRT reduces nitrogen pollution on all the soil distributions considered here (Table 3). Reductions of nitrogen pollution with the adoption of soil testing over the conventional application practices range from 9% on the low average fertility and quality soils to 34% on the high average fertility and quality soils. Total per acre pollution reductions with the adoption of both soil testing and VRT range between 12% and 55%. The analysis also indicates that the adoption of soil testing reduces nitrogen pollution more than the adoption of VRT, particularly on fields with low variability.

In order to examine the implications of output price uncertainty for the design of cost-share subsidies to achieve pollution reduction by accelerating adoption, we estimate cost-share subsidies required for immediate adoption of soil testing and VRT as a percentage of the capital costs of adoption. Ignoring uncertainty and irreversibility, the NPV rule indicates that there is no need to offer a cost share subsidy for inducing adoption of soil testing and VRT on most of the soil conditions considered here (Table 3).

When the possibility of stepwise adoption is recognized under the option value approach, the analysis illustrates that although a cost-share subsidy is not necessary to induce immediate adoption of soil testing large subsidies are needed to induce immediate adoption of VRT. The required subsidy for VRT varies depending on the soil conditions. No subsidy is needed to induce the adoption of VRT on fields with relatively high soil quality, high soil fertility and high spatial variability in one or both. These are also the fields on which adoption of VRT would achieve high rates of reduction in nitrogen pollution. Among the other soil conditions considered here, the pollution reduction per dollar of subsidy to adopt VRT is higher on fields with low soil quality but high variability in soil quality and/or those with high variability in soil fertility (last column of Table 3). A subsidy would be most effective at reducing pollution if targeted to these soil conditions.

Table 3 also presents the effects of ignoring the possibility of stepwise adoption on the required cost-share subsidies for immediate adoption. It indicates that there is a need to offer a cost-share subsidy to induce immediate adoption of both soil testing and VRT on many of the soil conditions considered here. Compared to the sequential decision making approach that offers different subsidy rates for soil testing and VRT, modeling SSCM as a package underestimates the required subsidy for immediate adoption of VRT while it overestimates the required subsidy for soil testing.

5. Conclusions

This paper developed a model to analyze the adoption of interrelated technologies when fixed costs can generate option values to delaying investment and some components of the technological package can be profitably adopted independently. Application of the model to SSCM reveals the extent to which recognition of option values and the possibility of piecemeal adoption influence forecasts about adoption. In the case of SSCM, the model that accounts for uncertainty using the option value approach and sequential adoption provides a better explanation for the observed rates and pattern of adoption of SSCM than models based on the net present value rule. The more sophisticated model also yields more precise policy implications concerning green subsidies.

The results of the empirical model indicate that economic benefits of both soil testing and VRT are greater on fields with relatively high quality and low fertility soils with high variability.

The results also illustrate that the NPV rule predicts that farmers prefer to adopt both soil testing and VRT at the same time under most of the soil conditions considered here. However, recognition of the possibility of stepwise adoption under output price uncertainty indicates that it is preferable to first adopt soil testing but delay investment in VRT for 2 to 17 years unless the average soil quality is high and the variability in soil quality and soil fertility is relatively high.

The paper shows that the reduction in nitrogen pollution with adoption of SSCM is higher on the high average quality and fertility soils with relatively high variability. On some of these soil conditions immediate adoption of VRT is privately profitable even under the sequential adoption approach. On other soil conditions, a cost-share subsidy could be used to accelerate adoption. Considering the possibility of stepwise adoption, the option value method indicates that while a cost-share subsidy is not necessary to induce immediate adoption of soil testing, a subsidy is needed to induce immediate adoption of VRT, particularly on soil conditions with low average soil quality. Cost-share subsidies to accelerate the adoption of VRT would be most effective at reducing nitrogen pollution if targeted towards fields with low average soil quality and high spatial variability in soil quality and/or soil fertility. Ignoring the possibility of stepwise adoption under the option value approach leads to underestimation of the required subsidy for adoption of VRT and overestimation of the required subsidy for soil testing.

Table 1. Quasi-Rents under Alternative Soil Fertility and Soil Quality Distributions

Soil Fertility		Discounted Average Annual Quasi-Rent ($ Per Acre)			Quasi-Rent Differential Over Conventional ($ Per Acre)		NPV Rule Adoption Decision[1]
Level	CVF (%)	Conventional	Soil Testing	Soil Testing+ VRT	Soil Testing	Soil Testing+ VRT	
LOW SOIL QUALITY WITH 25% CVQ							
LOW	30	216.6	222.0	231.1	5.4	14.5	A^S
	45	209.8	217.5	230.2	7.7	20.4	A
	60	204.4	214.1	228.8	9.7	24.4	A
HIGH	30	248.8	252.1	259.9	3.3	11.1	A
	45	238.2	242.5	255.2	4.2	16.9	A
	60	225.8	232.1	249.0	6.3	23.2	A
LOW SOIL QUALITY WITH 40% CVQ							
LOW	30	211.5	219.6	233.9	8.1	22.4	A
	45	205.3	215.5	233.1	10.3	27.8	A
	60	200.4	212.5	231.7	12.1	31.3	A
HIGH	30	245.6	249.6	260.6	4.0	15.0	A
	45	235.3	240.4	256.3	5.1	21.0	A
	60	223.8	230.5	250.9	6.7	27.1	A
HIGH SOIL QUALITY WITH 25% CVQ							
LOW	30	285.1	296.8	306.7	11.7	21.6	A
	45	276.2	294.2	306.7	18.2	30.5	A
	60	268.7	292.4	306.2	23.6	37.5	A
HIGH	30	316.9	324.2	335.8	7.3	18.7	A
	45	303.9	313.7	332.2	9.8	28.3	A
	60	289.7	302.1	327.0	12.4	37.3	A
HIGH SOIL QUALITY WITH 40% CVQ							
LOW	30	280.7	295.3	309.7	14.6	29.0	A
	45	272.2	293.0	309.6	20.8	37.4	A
	60	265.2	290.9	309.4	25.7	44.2	A
	30	313.2	332.4	336.2	9.2	23.0	A
HIGH	45	300.8	311.7	333.6	10.9	32.8	A
	60	287.4	300.4	329.6	13.0	42.2	A

Low soil fertility indicates that the average levels of Phosphorus and Potassium are 30 and 200lbs/acre, respectively. High soil fertility indicates that the average levels of Phosphorus and Potassium are 50 and 280lbs/acre, respectively.

Low soil quality indicates an average potential yield of 130 bushels/acre.

High soil quality indicates an average potential yield of 165 bushels/acre.

[1] In this column, A indicates that adoption of both soil testing and VRT is profitable while A^S indicates that adoption of only soil testing is profitable under the NPV rule

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

Soil Fertility		SSCM as a Package (Soil Testing+VRT)	Sequential Adoption		$\beta/(\beta-1)$		
Level	CVF (%)	(Year)	Soil Testing (Year)	VRT (Year)	Soil Testing	VRT	Soil Testing+ VRT
LOW SOIL QUALITY WITH 25% CVQ							
LOW	30	11	1	*	1.424	3.109	2.132
	45	2	1	11	1.802	2.716	2.236
	60	2	1	7	2.268	2.573	2.317
HIGH	30	16	1	*	2.120	2.726	2.292
	45	11	1	17	2.452	2.886	2.448
	60	2	1	11	2.455	2.970	2.569
LOW SOIL QUALITY WITH 40% CVQ							
LOW	30	1	1	7	2.097	2.205	1.909
	45	1	1	2	2.045	2.123	2.029
	60	1	1	1	2.735	2.265	2.335
HIGH	30	11	1	16	2.716	2.314	2.202
	45	7	1	7	2.588	2.514	2.277
	60	1	1	2	2.675	2.543	2.357
HIGH SOIL QUALITY WITH 25% CVQ							
LOW	30	2	1	*	1.584	3.880	2.019
	45	1	1	17	1.603	3.362	2.087
	60	1	1	16	1.797	3.087	2.167
HIGH	30	2	1	7	3.422	1.778	1.893
	45	1	1	1	2.620	1.887	2.001
	60	1	1	1	3.170	1.878	2.094
HIGH SOIL QUALITY WITH 40% CVQ							
LOW	30	1	1	11	1.542	2.664	1.854
	45	1	1	7	1.661	2.380	1.937
	60	1	1	1	1.735	2.265	1.939
HIGH	30	1	1	7	2.212	1.802	1.887
	45	1	1	1	2.775	1.794	1.950
	60	1	1	1	3.261	1.782	2.019

* indicates adoption is not profitable in the next 25 years

Table 3. Nitrogen Pollution and Cost-Share Subsidy Requirement for Immediate Adoption under Alternative Soil Fertility and Soil Quality Distributions

Soil Fertility		Pollution (Pounds Per Acre)	Pollution Reduction over Conventional Application Practices (%)		Cost Share Subsidy Required (% of capital costs)		Pollution Reduction in Pounds per Dollar Subsidy for VRT with Sequential Adoption
Level	CVF (%)	Conventional	Soil Testing	Soil Testing +VRT	SSCM as a Package (Soil Testing+ VRT)	Sequential Adoption VRT	
LOW SOIL QUALITY WITH 25% CVQ							
LOW	30	43.6	9.0	11.9	38.1	69.1	0.87
	45	45.7	12.5	16.3	16.6	50.5	1.69
	60	47.4	15.2	19.4	4.1	39.5	2.68
HIGH	30	40.6	10.6	16.2	59.5	71.1	0.94
	45	44.1	15.1	19.9	39.1	54.5	1.86
	60	47.9	19.8	25.4	19.4	40.4	3.48
LOW SOIL QUALITY WITH 40% CVQ							
LOW	30	45.2	12.6	22.1	-	37.4	3.05
	45	47.1	15.6	25.8	-	13.0	10.72
	60	48.7	18.0	28.3	-	-	-
HIGH	30	41.8	13.2	22.6	40.8	51.8	2.09
	45	44.9	17.1	27.6	18.4	34.5	4.11
	60	48.5	21.2	32.4	-	15.9	11.38
HIGH SOIL QUALITY WITH 25% CVQ							
LOW	30	30.1	18.4	23.6	2.1	72.6	1.14
	45	32.8	25.6	31.3	-	59.9	1.98
	60	35.1	30.5	36.3	-	20.3	7.21
HIGH	30	27.1	20.4	29.2	12.5	35.9	2.54
	45	31.1	26.4	37.8	-	-	-
	60	35.5	32.1	44.6	-	-	-
HIGH SOIL QUALITY WITH 40% CVQ							
LOW	30	31.4	22.3	38.7	-	42.4	3.29
	45	34.1	28.6	44.8	-	23.7	7.44
	60	36.2	32.9	48.9	-	-	-
HIGH	30	28.3	23.4	42.3	-	21.9	6.31
	45	32.1	28.3	49.5	-	-	-
	60	36.2	33.7	55.3	-	-	-

- indicates cost share subsidy is not necessary.

References

Barry, D.A.J., D. Goorahoo and M.J. Goss, 1993, "Estimation of Nitrate Concentration in Groundwater Using a Whole Farm Nitrogen Budget". *Journal of Environmental Quality*, 22 (October-December): 767-775.

Babcock, B.A., A. L. Carriquiry and H. S. Stern, 1996, "Evaluation of Soil Test Information in Agricultural Decision-making", *Applied Statistics*, (45)4: 447-461.

Babcock, B.A., G.R. Pautsch, 1998, "Moving from Uniform to Variable Fertilizer Rates on Iowa Corn: Effects on Rates and Returns", *Journal of Agricultural and Resource Economics*, 23(2):385-400.

Bar-Ilan, A., W. Strange, 1998, "A model of Sequential Investment" *Journal of Economic Dynamics and Control*, 22(3), pp. 437-63.

Caswell, M.F., D. Zilberman and G. Casterline, 1993, "The Diffusion of Resource-Quality-Augmenting Technologies: Output Supply and Input Demand Effects," *Natural Resource Modeling*, 7(4): 305-329.

Dai, Q. J.J. Fletcher, and J.G., Lee, 1993, "Incorporating Stochastic Variables in Crop Response Models: Implications for Fertilization Decisions", *American Journal of Agricultural Economics*, 75 (May 1993):377-386.

Dickey, D. A. and W. A. Fuller, 1981, "Likelihood Ratio Statistics for Autoregressive Time Series with a Unit Root", *Econometrica*, 49(4): 1057-1072.

Dixit, A. K. and R.S. Pindyck, 1994, Investment Under Uncertainty, Princeton University Press, Princeton, NJ.

Feder, G., 1982, "Adoption of Interrelated Agricultural Innovations: Complementarily and the Impacts of Risk, Scale, and Credit" *American Journal of Agricultural Economics*, 64 (1982), 94-101.

Frank, M. D., B. R. Beattie, M. E. Embleton, 1990, "A Comparison of Alternative Crop Response Models, "*American Journal of Agricultural Economics*; 72(3): 597-603.

Khanna, M., O. F. Epouhe, and R. Hornbaker, 1999a, "Site-Specific Crop Management: Adoption Patterns and Trends," *Review of Agricultural Economics*, Fall/Winter.

Khanna, M., M. Isik, A. Winter-Nelson, 1999b, "Investment in Site-Specific Crop Management Under Uncertainty: Implications for Nitrogen Pollution Control", Program of Environmental and Resource Economics working paper #18, University of Illinois.

Leathers, H.D. and M. Smale, 1991, "A Bayesian Approach to Explaining Sequential Adoption of Components of a Technological Package", *American Journal of Agricultural Economics*, (August 1991), 734-742.

Illinois Agronomy Handbook, 1998, University of Illinois at Urbana-Champaign, Department of Crop Sciences, Cooperative Extension Service.

Olson, K.R., K. R. and J. M. Lang, 1994, Productivity of Newly Established Illinois Soils, 1978-1994, Supplement to Soil Productivity in Illinois, Department of Agronomy, University of Illinois at Urbana-Champaign.

Price, T.J. and M. E. Wetzstein, 1999, "Irreversible Investment Decisions in Perennial Crops with Yield and Price Uncertainty", *Journal of Agricultural and Resource Economics*; v24, n1, July 1999, pp. 173-85.

Purvis, A., W. G. Boggess, C. B. Moss, and J. Holt, 1995, "Technology Adoption Decisions Under Irreversibility and Uncertainty: An Ex Ante Approach", *American Journal of Agricultural Economics,* 77 (August 1995): 541-551.

Ray, D. E., J. W. Richardson, D. G. De La Torre Ugarte, and K. H. Tiller, 1998, "Estimating Price Variability in Agriculture: Implications for Decision Makers", *Journal of Agricultural and Applied Economics*, 30(1): 21-33.

Schnitkey, G. D., J.W. Hopkins, and L.G. Tweeten, 1996, "An Economic Evaluation of Precision Fertilizer Applications on Corn-Soybean Fields" in Proceedings of the Third National Conference on Precision Agriculture, June 23-26, 1996, edited by P.C. Robert, R.H. Rust, and W.E. Larson, 1996, American Society of Agronomy.

Thrikawala, S., A. Weersink, G. Kachnoski, and G. Fox, 1999, "Economic Feasibility of Variable Rate Technology for Nitrogen on Corn", *American Journal of Agricultural Economics*, Vol. 81, No.4, November 1999.

USDA, *Agricultural Statistics*, National Agricultural Statistics Service, http://www.usda.gov/nass/pubs/histdata.htm, Government Printing Office, Washington DC (annual issues, 1965-98).

Watkins, K.B., Y. Lu, and W. Huang, 1998, "Economic and Environmental Feasibility of Variable Rate Nitrogen Fertilizer Application with Carry-Over Effects", *Journal of Agricultural and Resource Economics*, 23(2): 401-426.

Winter-Nelson, A. and K. Amegbeto, 1998, "Option Values to Conservation and Agricultural Price Policy: Application to Terrace Construction in Kenya", *American Journal of Agricultural Economics*, 80 (May 1998), 409-418.