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Sequential Investment in Site-Specific Crop Management Under Output Price Uncertainty

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An option-value model is developed to analyze the impacts of output price uncertainty, high sunk costs of adoption, and site-specific conditions on the optimal timing of adoption of two interrelated site-specific technologies, soil testing and variable rate technology (VRT). The model incorporates the potential for adopting these two technologies jointly or sequentially. The implications of the pattern of adoption for nitrogen pollution and for the design of a cost-share subsidy policy to accelerate the adoption of these technologies to reduce nitrogen pollution are also analyzed. Ignoring the potential for sequential adoption would tend to underpredict the adoption of soil testing and overpredict the adoption of VRT. Cost-share subsidies to induce accelerated adoption of VRT would be most effective at reducing nitrogen pollution if targeted toward fields with relatively high spatial variability in soil quality or soil fertility, and either low average soil quality or low average soil fertility.

Key words: agricultural technologies, cost-share subsidy, nitrogen pollution, option value, price uncertainty, spatial variability

Introduction

Conventional farm management practices apply nitrogen and other fertilizers uniformly across fields. Because the fertility and quality of soils tend to vary within a field, these practices can lead to overapplication of chemicals and high levels of nitrate runoff in at least some parts of the field. Recent technological advances in site-specific crop management (SSCM) make it possible for farmers to acquire detailed information about the spatial characteristics of their fields and target fertilizer applications to meet spatially varying needs. Variable fertilizer applications have 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 either 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 study presents a method to analyze adoption of interrelated components of a technology under output price uncertainty and applies that method to analyze mechanisms to encourage adoption of SSCM to achieve environmental objectives.

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SSCM relies on several interrelated technologies that can be adopted sequentially. These include diagnostic tools such as grid-based soil testing to gather information about soil conditions in the field and the variable rate technology (VRT) used for applying fertilizer at a varying rate on-the-go within the field to meet location-specific needs. Soil testing provides information about the nutrient needs of the soil and can be used to improve the choice of uniform rate of fertilizer application (Babcock and Blackmer). Likewise, soil testing results can reveal how the rate of fertilizer application in the field should be spatially varied. Farmers, therefore, have a choice of either undertaking soil testing and delaying or not adopting VRT, or adopting SSCM as a package by adopting VRT immediately after soil testing.

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 (Khanna, Epouhe, and Hornbaker). For example, 37% of farmers surveyed in the Midwest had adopted soil testing, but only 12% had adopted VRT. Uncertainties about the returns from SSCM and its high costs of adoption ranked as two important reasons for nonadoption by a majority of the farmers.

Uncertainties about the returns from adoption of SSCM could arise for several reasons, such as uncertainty about output prices, yields, and weather, and about the ability of the technology to accurately measure soil variability. While returns from SSCM are uncertain, investment in some components involves high sunk costs. Because 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 were to be liquidated due to declining revenues. In this investigation, we focus on the implications of output price uncertainty for irreversible investment in SSCM.

Many studies have analyzed the economic and environmental impacts of adoption of soil testing (Schnitkey, Hopkins, and Tweeten; Babcock, Carriquiry, and Stern) or SSCM as a technology package (Thrikawala et al.; Schnitkey, Hopkins, and Tweeten; Watkins, Lu, and Huang; Babcock and Pautsch). These studies treat adoption as a one-time decision and rely on the 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 (e.g., Feder; Leathers and Smale) apply a Bayesian/learning approach to 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. The Bayesian approach is useful for analyzing decision making in situations where the uncertainty can be characterized by a probability distribution which is updated and made more precise by using information acquired because of adopting a new technology. However, when uncertainties are characterized by a stochastic process, irreversible investment decisions are involved, and farmers have flexibility in the timing of adoption, an option-value framework is more appropriate. The option-value method allows analysis not only of the question of whether to adopt but also of when to adopt.

A growing body of work has applied the option-value approach to explain the timing of adoption of agricultural technologies (Purvis et al.; Winter-Nelson and Amegbeto; Price and Wetzstein; Khanna, Isik, and Winter-Nelson). These papers, however, analyze the 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.

Our study has three objectives. First, we adapt the option-value approach (Dixit and Pindyck) to address situations in which there is output price uncertainty, high sunk costs, and the possibility to adopt separate components of a technology piecemeal, sequentially, or simultaneously.[1] Second, we use an example of SSCM technologies to illustrate how analysis based on the NPV rule and analysis that ignores piecemeal adoption within the option-value approach can misrepresent the returns to technology adoption. Third, we demonstrate the potential policy relevance of considering piecemeal adoption by examining the design of cost-share subsidies to achieve pollution reduction by accelerating adoption of SSCM. The optimal targeting of these subsidies across heterogeneous soil conditions is analyzed, as well as how these subsidies should differ in their incentives for adoption of soil testing and VRT.

The remainder of the article is organized as follows. The next section develops the theoretical framework to analyze sequential investment decisions. Data used in the numerical simulation are then described, followed by a discussion of the results of the simulation. Our conclusions are provided in the final section.

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). We assume a deterministic, constant returns-to-scale crop response function and represent the yield per acre (y) at any time (t) as a function of the soil fertility level per acre z and the applied input per acre x. This function is represented by $y_t = f(z_t, x_t)$, with $f_z > 0$, $f_x > 0$, $f_{zz} < 0$, and $f_{xx} < 0$.[2]

The farmer has a discrete choice among three alternatives: (a) using the conventional practices, (b) adopting soil testing only, or (c) adopting both soil testing and VRT.[3] 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 markets. 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 cost of adoption of both soil testing and VRT is represented 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, implying 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 VRT equipment is $\overline{T}$ years, and the discount rate is ρ.

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[1] The analysis could be extended to include other sources of uncertainty such as yield, weather, or technology. To keep the analysis tractable, while illustrating the effect of uncertainty on the incentives for sequential adoption, we focus only on output price uncertainty.

[2] Because we are assuming that time is a continuous variable, the time-dependent variables should be denoted as $x(t)$. However, for ease of exposition, we are denoting them as x_t.

[3] The framework can be expanded to include a continuum of alternatives, such as adopting soil testing and varying inputs within the field at a less fine scale than is possible with VRT. Little additional insight is expected, however, on the motivations for sequential versus one-step adoption, while the costs in terms of analytical complexity would be substantial.

In order to examine the environmental implications of SSCM, we assume a portion of the applied input is absorbed by the crop and converted into dry grain matter, θy_t (following Barry, Goorahoo, and Goss; Thrikawala et al.). The remainder of the applied input may be carried over in the soil and change the level of soil fertility by $\dot{z}$ per acre and/or generate polluting runoff (R_t) per acre:

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

Decision Problem Under Certainty

The profit-maximizing 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 costs of adoption. This decision involves forecasting the profit-maximizing stream of expected returns with the conventional practices, with soil testing alone, and with both soil testing and VRT, and then comparing these forecasts to one another and the fixed costs of adoption.

Under conventional 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. This approach to determining the input application rate is also referred to as the averaging approach (Schnitkey, Hopkins, and Tweeten; Babcock and Pautsch). The farmer then assumes μ is the soil fertility level in the entire field and chooses a single level of input application per acre for the whole field by maximizing the discounted value of expected quasi-rents, π_0^C, as follows:

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

where E denotes the expectations operator based on the subjective probability distribution of future prices given the information available at time $t = 0$. The profit-maximizing input rate is determined such that $\partial\pi_0^C/\partial x_t = E(P_t) f_x(x_t, \mu_t) - w = 0$, and is represented by $x_t^C = x(E(P_t), w, \mu_t)$.

Soil testing provides information about the distribution of soil fertility within the field, $g(z)$. This makes it possible for the farmer to improve upon the conventional uniform application rate which was based on information about only one of the parameters, μ, of the distribution $g(z)$. Knowledge of $g(z)$ leads to a new uniform rate for the whole field to maximize the expected value of discounted quasi-rents, π_0^S, as follows:

$$\pi_0^S = \max_{x_t} \int_0^T e^{-\rho t} \left[\int_l^u A\Big(E(P_t) f(x_t, z_t) - w x_t\Big) g(z)\, dz \right] dt. \tag{3}$$

The profit-maximizing uniform input application per acre, given $g(z)$, is determined such that $\partial\pi_0^S/\partial x_t = \int_l^u (E(P_t) f_x(x_t, z_t)) g(z)\, dz - w = 0$, and is represented by $x_t^S = x(E(P_t), w, g(z))$. This input rate could be higher or lower than the input rate under the conventional technology depending on the distribution of soil fertility.

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 input application rate x_t is now chosen given the site-specific level of soil fertility z_t at each point in the field to maximize the discounted quasi-rents as follows:

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

The input level at any point in the field is determined such that $\partial\pi_0^B/\partial x_t = E(P_t)f_x(x_t, z_t) - w = 0$ for each z, and depends on the soil fertility level at that point; thus, $x_t^B = x(E(P_t), w, z_t)$. This rate would vary continuously across the field as z_t varies.

The input levels for each technology are obtained from the first-order conditions of (2), (3), and (4) to find the maximum values of the discounted quasi-rents π_0^{C*}, π_0^{S*}, and π_0^{B*}. The present value of the quasi-rent differential from adopting soil testing only is denoted by $N_0^S(P, w, g(z), \overline{T}, A) = \pi_0^{S*} - \pi_0^{C*}$, while the corresponding present value from adopting both components is denoted by $N_0^B(P, w, g(z), \overline{T}, A) = \pi_0^{B*} - \pi_0^{C*}$. By disaggregating the quasi-rent differential due to adoption of both soil testing and VRT, we obtain the quasi-rent differential due to adoption of VRT: $N_0^V = N_0^B - N_0^S$.

The quasi-rent differentials (N_0^B, N_0^V, and N_0^S) are always positive as long as there is any variability in soil conditions within the field, because input choice with either soil testing or VRT is based on more information and fewer constraints on the application rate as compared to the conventional practice. This is because soil testing provides information about the distribution of soil fertility within the field and enables the farmer to choose a uniform input application rate x_t^S to maximize his/her quasi-rents. Because the option of choosing x_t^C is always available to the farmer, even after soil testing, quasi-rents with soil testing must be at least as high as those under the conventional practice.

Hennessy and Babcock show that the quasi-rent differential N_0^S is always positive as long as there is variability in soil fertility within the field. By adopting VRT and choosing a different rate for each of the different plots in the field, quasi-rents can be further increased relative to conventional practices because the farmer is no longer constrained to apply a uniform rate across the field (as reported by Khanna, Isik, and Winter-Nelson; Babcock and Pautsch). The above studies show that the quasi-rent differentials (N_0^S, N_0^V, and N_0^B) increase when the variability in the soil fertility distribution increases. However, these differentials may not always be larger than the fixed costs of adopting S, V, or B, respectively. Under the NPV rule, it would appear optimal to adopt both soil testing and VRT 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. To keep our analysis tractable, we assume these quasi-rent differentials evolve as a geometric Brownian motion:

$$(5) \qquad dN^j = \alpha^j N^j dt + \sigma^j N^j dz^j, \quad j = S, V, B,$$

where dz is the increment of a Wiener process with mean zero and unit variance, α is the drift parameter, and σ is the volatility in the drift parameter. Equation (5) implies that changes in the positive quasi-rent differentials N^j are lognormally distributed; that is, changes in the logarithm of the difference in quasi-rents relative to conventional practices are normally distributed.

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 the sequential nature of the two decisions. The 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 $\tilde{T}$ by maximizing the discounted net returns of VRT. Net returns are defined as the difference between the quasi-rent differential and the fixed costs of adoption of VRT, and are represented by:

$$F^V\left(N_T^V\right) = E\left[\left(N_T^V - K_T^V\right)e^{-\rho T}\right]. \tag{6}$$

The optimized value of $F^V(N_T^V)$ in (6), denoted by $F^V(N_{\tilde{T}}^V)$, 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, (6) is maximized subject to (5), with $j = V$. Use of dynamic programming reveals it is optimal to invest in VRT at $\tilde{T}$ when the critical value of the quasi-rent differential is (Dixit and Pindyck):

$$N_{\tilde{T}}^{V*} = \frac{\beta^V}{\beta^V - 1} K_{\tilde{T}}^V, \tag{7}$$

where

$$\beta^V = \frac{1}{2} - \frac{\alpha^V}{(\sigma^V)^2} + \sqrt{\left(\frac{\alpha^V}{(\sigma^V)^2} - \frac{1}{2}\right)^2 + \frac{2\rho}{(\sigma^V)^2}} > 1.$$

Thus the investment rule under uncertainty and irreversibility requires N_T^V to be greater than K_T^V by a factor of $\beta^V/(\beta^V - 1)$. We refer to this factor as the option-value multiple for VRT. This multiple is a positive function of the growth rate (α^V) and the volatility of the growth rate in N_T^V, σ^V, and a negative function of the discount rate. It varies with the characteristics of the soil distribution. Because $K_{\tilde{T}}^V = K_0^V e^{-\delta^V \tilde{T}}$, an increase in δ^V results in a lower critical value of the quasi-rent differential in the future and makes adoption more likely in the future even if it is not optimal immediately.

Given $F^V(N_{\tilde{T}}^V)$, the optimal time to invest in soil testing is found by maximizing the net returns from soil testing subject to (5), with $j = S$, as follows:

$$F^S\left(N_T^S\right) = E\left[\left(N_T^S - K_T^S\right)e^{-\rho T}\right] + F^V\left(N_T^V\right). \tag{8}$$

The solution to the maximization problem in (8) shows 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

$$N_{\hat{T}}^{S*} = \frac{\beta^S}{\beta^S - 1}\left(K_{\hat{T}}^S - F^V\left(N_{\tilde{T}}^V\right)\right). \tag{9}$$

The critical value of the quasi-rent differential required for investment in soil testing increases with an increase in $\beta^S/(\beta^S - 1)$, an increase in the fixed costs of soil testing, and a decrease in the value of the option to invest in VRT. The optimal values $\hat{T}$ and $\tilde{T}$ represent the expected time of adoption of soil testing and VRT, respectively, given stochastic returns.

The anticipation of high returns from subsequent adoption of VRT could create incentives for investment in soil testing even when the quasi-rent differential due to soil testing is less than its fixed costs. Anticipated high returns lower the critical value of quasi-rents required to induce adoption of soil testing. 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 until $\tilde{T}$. 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 ignoring the possibility of adopting the components stepwise imposes the constraint that $\tilde{T} = \hat{T}$. This constrains the adoption of VRT to occur immediately after the adoption of soil testing, and 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 (5), with $j = B$:

$$F^B\left(N_T^B\right) = E\left[\left(N_T^B - K_T^B\right)e^{-\rho T}\right]. \tag{10}$$

The solution to (10) shows that the critical value of the quasi-rent differential at which it is optimal to invest in the SSCM package is

$$N_T^{B*} = \frac{\beta^B}{\beta^B - 1} K_T^B. \tag{11}$$

A cost-share subsidy may be used to induce adoption when it is not otherwise optimal to invest immediately. Under the NPV rule, the required cost-share subsidy for immediate investment is the difference between the present value of the 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 specified as:

$$H^S = K_0^S - \frac{\beta^S - 1}{\beta^S} N_0^S - F^V\left(N_0^V\right). \tag{12}$$

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

$$H^V = K_0^V - \frac{\beta^V - 1}{\beta^V} N_0^V. \tag{13}$$

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:

$$H^B = K_0^V + K_0^S - \frac{\beta^B - 1}{\beta^B}\left(N_0^V + N_0^S\right). \tag{14}$$

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 the option-value multiples for soil testing and VRT and $F^V(N_T^V)$. These subsidy estimates vary with the distribution of soil characteristics influencing the value of the option-value multiple. In the following section, we analyze the potential for sequential adoption and irreversibility to affect policy results using a simulation model of corn production in Illinois.

Empirical Analysis

The empirical analysis considers variable application of 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. Each 2.5-acre plot is tested and assumed to have homogeneous soil conditions. Soil tests provide information about the levels and variability in two attributes of the soil—soil fertility and soil quality.[4] 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 nitrogen levels 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 Cooperative Extension Service (CES)]. Nitrogen requirements of the crop depend on the quality of the soil as represented by its maximum potential yield. Consequently, nitrogen application rates under SSCM vary with variations in the maximum potential yield across a field; in the other systems, however, nitrogen application is uniform across the field based on average soil quality in the field.

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 Dai, Fletcher, and Lee). The distributions of soil nutrient levels and soil quality are determined by a random draw of numbers. Alternative soil conditions are simulated by changing the means and variances of the Beta distributions, using the same random number seed. Two alternative mean levels (low and high) of soil fertility are considered with three alternative coefficients of variation (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 fertilizers (consistent with Schnitkey, Hopkins, and Tweeten; Dai, Fletcher, and Lee). We estimated the production function parameters using data from the *Illinois Agronomy Handbook* (Illinois CES) for given levels of the maximum yield potential. This function assumes maximum yield is attainable when all soil nutrients are available in appropriate amounts in the soil, and a shortfall in even one input can act as a limiting factor to the attainment of the maximum yield potential. Information on percentage of potential yield obtained during field experiments with various levels of each of the three fertilizer inputs (nitrogen, potassium, and phosphorous), while keeping the other two fertilizers at unconstrained amounts, was used to calculate coefficients for the production function that best fit the observed data. We obtained the following functional relationship:

$$y_i = h_i\left(1 - e^{-(0.51+0.025x_{in})}\right)\left(1 - e^{-(0.28+0.1(x_{ip}+z_{ip}))}\right)\left(1 - e^{-(0.115+0.012(x_{ik}+z_{ik}))}\right), \tag{15}$$

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[4] Adoption of SSCM may not completely eliminate uncertainty about soil nutrient levels due to measurement errors in soil sampling and testing. It is likely that the inclusion of this uncertainty in our analysis would reduce the quasi-rent differential and the extent of nitrogen pollution reduction due to adoption. The quasi-rent differentials and pollution reduction rates reported should therefore be considered as potential benefits.

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 $i = 1, \ldots, 200$.

The soil fertility carryover equation (1) for phosphorus and potassium is calibrated based on recommendations provided in the *Illinois Agronomy Handbook* (Illinois CES). Applied phosphorus and potassium in excess of amounts absorbed by plants are carried over by the soil, raising soil fertility levels for the next crop.[5] In the case of nitrogen, we assume that 0.75 pounds of applied nitrogen are absorbed by a bushel of corn, and that all excess nitrogen in the soil is available for leaching (Barry, Goorahoo, and Goss).

SSCM is defined here to include soil testing and sampling that is done once in four years, as well as the adoption of VRT and yield monitors. Information from soil testing is used to determine spatially varying input applications with VRT. We assume the farmer tracks changes in the spatial variability in soil conditions by using a yield monitor 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 ($1.6/acre/year), while the cost of the yield monitor with a GPS receiver and the VRT equipment is $7,855 and $12,345, respectively.[6] The 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 of $1,125.

The total cost of the VRT components is $22,243. Assuming a five-year lifetime and a 5% discount rate, this amounts to an average annual per acre cost of about $8.9. The total cost of adopting both soil testing and VRT is $25,425 ($10.2/acre/year). The cost of SSCM is expected to decline as growing demand leads to economies of scale in manufacturing. Indeed, a declining trend in the equipment costs is already being observed. The costs of Ag Leader yield monitors and GPS receivers fell by about 10% between 1997 and 1999. Hence, total 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. Prices of nitrogen, phosphorus, and potassium are assumed to be at their 1997 levels of $0.20/pound, $0.24/pound, and $0.13/pound, respectively.

The stochastic nature of the quasi-rent differentials in (5) is assumed to arise from uncertainty in the output prices. Because the corn-price process is shown to be nonstationary (see Khanna, Isik, and Winter-Nelson), we model the output price process as a geometric Brownian motion represented by the following discrete approximation (Dixit and Pindyck, p. 72):

$$(16) \qquad P_t = (1 + \gamma)P_{t-1} + \lambda P_{t-1} v_t,$$

where γ is the drift parameter, λ is the standard deviation in the drift parameter, and v_t is a normally distributed random variable with mean zero and unit variance. The parameters of the geometric Brownian motion are obtained as in Forsyth. The drift parameter is estimated as $\gamma = m + (0.5)\lambda^2$, where m is the mean of the series $\ln(P_{t+1}/P_t)$ and λ is the standard deviation of the series. Using historical data on real corn prices over the period 1926–1998 (U.S. Department of Agriculture), the value of γ is found to be -0.014. The standard deviation of the average annual percentage change λ is estimated to be 0.223.

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[5] Phosphorus and potassium are not mobile nutrients and usually remain in the soil and contribute to environmental contamination only through soil erosion (Illinois CES; Schnitkey, Hopkins, and Tweeten).

[6] Costs of soil sampling and testing were provided by Illini FS, Inc., Agricultural Cooperative; costs of yield monitors with GPS and VRT were provided by Ag Leader Technology, Inc., and Ag-Chem Equipment Co., Inc., respectively.

This process [equation (16)] is used to forecast prices for a 25-year period by assigning random values to v_t. Geometric Brownian motion of output prices justifies the assumption of the stochastic process followed by the quasi-rent differentials N_T^j. The randomly realized path of prices for the 25-year period is used to forecast the discounted quasi-rent differentials if adoption were to occur in each of the $T = 1, \ldots, 25$ years for each soil distribution. For each of these series of N_T^j estimated for 25 years for each of the assumed soil fertility and soil quality distributions, we then estimate α^j and σ^j to characterize the stochastic process in (5) and to determine the option value using (7) and (9).

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 over the five-year lifetime of the equipment with the conventional practices, soil testing, and both soil testing and VRT are summarized in table 1. Quasi-rents with all three adoption decisions increase as average soil fertility within the field increases because there is a reduced need for fertilizer. Quasi-rents also increase with an increase in the average level of soil quality because the marginal productivity of inputs is increased.

The adoption of both soil testing and VRT leads to an increase in quasi-rents, relative to those with the conventional practices, for all soil fertility and soil quality distributions, as expected from the theoretical analysis above (table 1). As average soil quality increases, the uniform application rate rises for all inputs under the conventional practices. This increases costs more than it increases yields per acre, and thus the gains in quasi-rent with adoption of one or both components of SSCM increase. An increase in the average level of soil fertility, on the other hand, reduces the quasi-rent differential of both soil testing and VRT because 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. Higher average soil quality, lower average soil fertility, and higher variability in soil quality and fertility lead to higher quasi-rent differentials. Our results are consistent with the findings of other simulation studies examining 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 analysis shows the importance of considering a combination of soil attributes when assessing the quasi-rent differential because some of these soil attributes interact in opposing ways.

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

Soil Fertility		Discounted Average Annual Quasi-Rent ($/acre)			Quasi-Rent Differential over Conventional ($/acre)		
Level	CVF[a] (%)	Conventional	Soil Testing	Soil Testing + VRT	Soil Testing	Soil Testing + VRT	NPV Rule Adoption Decision[c]
LOW SOIL QUALITY WITH 25% CVQ[b]							
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*
HIGH	30	313.2	332.4	336.2	9.2	23.0	*A*
	45	300.8	311.7	333.6	10.9	32.8	*A*
	60	287.4	300.4	329.6	13.0	42.2	*A*

Notes: Under low soil fertility, the average levels of phosphorus and potassium are 30 pounds/acre and 200 pounds/acre, respectively; under high soil fertility, the average levels of phosphorus and potassium are 50 pounds/acre and 280 pounds/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.

[a] CVF refers to coefficient of variation in the distribution of phosphorus and potassium.

[b] CVQ refers to coefficient of variation in the distribution of soil quality.

[c] *A* indicates that adoption of both soil testing and VRT is profitable under the NPV rule, while A^S indicates that adoption of only soil testing is profitable.

Additionally, in this study we disaggregate the quasi-rent differential with adoption of both soil testing and VRT into the proportions represented by each of the respective 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 in discounted average annual quasi-rents 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 average annual discounted cost of adopting soil testing is only \$1.6 per acre. Consequently, the NPV rule would predict the adoption of soil testing is profitable on all the soil conditions considered here. The average annual quasi-rent differentials of adopting both soil testing and VRT range between \$11.1 per acre and \$44.2 per acre on these soils. Because the per acre annual discounted cost of soil testing and VRT is about \$10.2 per acre, the NPV rule suggests it is optimal to adopt both soil testing and VRT.

The total discounted quasi-rent differentials of both soil testing and VRT over the five years exceed the total fixed costs of adoption on most of the soil conditions considered here. As shown in table 1, according to the NPV rule, adoption of both soil testing and VRT is preferred to the conventional practices on all the soil conditions except on the soils with low average quality, coefficient of variation in the soil quality of 25%, and coefficient of variation in the soil fertility distribution of 30%. 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, and whether it is optimal to adopt SSCM as a package or sequentially for each of the soil distributions considered here. With uncertain prices, there might be a value to waiting and observing prices in the future before incurring sunk costs to avoid a loss if prices were to fall in the immediate future. The timing of investment depends on the realizations of random prices. High realizations of prices signal higher future expected prices and a higher expected quasi-rent differential, which reduces the chance an investment will be lost and thus increases the expected returns from the investment. Low realized prices signal the need to wait longer.

The ex ante optimal timing of adoption of soil testing and VRT for a randomly obtained price path is found by calculating the critical value of the quasi-rent differential required for investment and comparing it to the expected quasi-rent differential in each of the 25 years for each soil fertility and soil quality distribution. The method for determining the critical value of the quasi-rent differential required for investment in soil testing and VRT is presented in (7) and (9).

The estimates of the option-value multiples for VRT and soil testing are reported in table 2. These option-value multiples determine the degree to which the quasi-rent differential must exceed the investment costs before investment will occur, given uncertainty and sunk costs. The estimates of the option-value multiples vary with the distribution of soil characteristics within the field, indicating the role of soil characteristics in mitigating the effects of uncertainty on the adoption decision. As the variability in soil fertility and quality increases, this factor increases for soil testing but decreases for VRT. This dynamic occurs because increased variability in soil conditions increases the benefits of VRT and reduces the relative gains from soil testing alone. The option-value multiple for soil testing ranges from 1.4 on low average fertility and quality soils to 3.4 on high average fertility and quality soils. The option-value multiple for VRT ranges from 1.7 on high average fertility soil to 3.8 on low average fertility soil.

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

Soil Fertility		SSCM as a Package:	Sequential Adoption		Option-Value Multiple		
Level	CVF[a] (%)	Soil Testing + VRT (year)	Soil Testing (year)	VRT (year)	Soil Testing	VRT	Soil Testing + VRT
			Low Soil Quality with 25% CVQ[b]				
Low	30	11	1	—[c]	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

[a] CVF refers to coefficient of variation in the distribution of phosphorus and potassium.
[b] CVQ refers to coefficient of variation in the distribution of soil quality.
[c] Indicates adoption is not profitable in the next 25 years.

Table 2 reveals that 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. On most of the other soil distributions, it is optimal to delay the adoption of VRT and adopt it sequentially. This is because high option values to VRT create critical threshold values of net returns which are much higher than the quasi-rent differentials. Unlike the NPV rule, the option-value rule forecasts delay of up to 17 years before adopting VRT on most of the soil distributions. These results on the timing of adoption are robust to changes in the discount rate from 5% to 10%. The option-value approach also forecasts delaying adoption of VRT for at least 25 years on the soil distributions with low soil quality and low variability in soil quality.[7] The decision rule suggests more waiting on the high average fertility and the low average quality soils with low variability in both. As the variability in these characteristics increases, the waiting time decreases substantially.

When the decision rule is constrained to require 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 option-value multiple for the package (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. Thus, considering SSCM as a package may underestimate the critical value of the quasi-rent differential at which it is optimal to adopt VRT, while it may overestimate the critical value of the quasi-rent differential of soil testing. Imposing simultaneous adoption therefore tends to predict earlier adoption of VRT than is predicted by the sequential analysis, particularly on soil distributions with low average quality and fertility (as shown in column 2 of table 2).

The timings of adoption obtained here for each of the components are meant to be illustrative rather than definitive. This analysis illustrates how uncertainty about the quasi-rent differential from adoption creates incentives to delay adoption, particularly of the component (VRT) involving high sunk costs. The analysis also shows how these incentives vary with soil distributions.

Implications of Soil Testing and VRT for Nitrogen Pollution Control

The impacts of adoption of soil testing and VRT on nitrogen, potassium, and phosphorus application rates and crop yield are used to determine the impact on pollution (summarized in table 3). Adoption of soil testing and VRT reduces nitrogen application per acre while increasing yield per acre, and therefore reducing nitrogen pollution relative to levels under the conventional practices on all soil distributions considered. The extent to which these changes occur varies across soil distributions. For example, on soil distributions with low soil fertility, low soil quality, and CVF of 30% and CVQ of 25%, pollution falls by 11.9% due to adoption of soil testing and VRT; soil testing accounts for a 9% reduction, and VRT contributes an additional 2.9% reduction. In contrast, on fields with high average fertility, low soil quality, and CVF of 60% and CVQ of 40%, the reduction in pollution due to soil testing and VRT is 32.4% (with soil testing alone leading to a reduction of 21.2%).

As the variability in soil fertility and soil quality increases, the extent of nitrogen pollution reduction due to adoption of one or both technologies increases. Reductions of nitrogen pollution with the adoption of only soil testing range from 9% on the low average fertility and quality soils to 34% on the high average fertility and quality soils. Total pollution reductions with the adoption of both soil testing and VRT range between 12% and 55%. The adoption of only soil testing reduces nitrogen pollution more than the additional pollution reduction obtained with adoption of VRT, particularly on fields with low variability.

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[7] The optimal timing of adoption with custom hiring of VRT as opposed to owner purchase of VRT is also analyzed. Custom hiring of VRT reduces but does not completely eliminate the sunk costs of adoption, because several components such as yield monitors need to be owner-purchased, while others such as soil testing involve one-time sunk costs. Hence, it is still optimal to adopt soil testing and VRT sequentially; the waiting time to custom hiring VRT lies between 2 and 11 years.

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

Soil Fertility		Pollution (lbs./acre)	Pollution Reduction over Conventional Practices (%)		Cost-Share Subsidy Required (% of capital costs)		Pollution Reduction in Pounds/$ Subsidy for VRT with Sequential Adoption
Level	CVF[a] (%)	Conventional	Soil Testing	Soil Testing + VRT	SSCM as a Package: Soil Testing + VRT	Sequential Adoption VRT	
LOW SOIL QUALITY WITH 25% CVQ[b]							
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	—[c]	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	—	—	—

[a] CVF refers to coefficient of variation in the distribution of phosphorus and potassium.

[b] CVQ refers to coefficient of variation in the distribution of soil quality.

[c] Indicates cost-share subsidy is not necessary.

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 (table 3). Ignoring uncertainty and irreversibility, the NPV rule indicates 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.

When the possibility of stepwise adoption is recognized under the option-value approach, no cost-share subsidy is required to induce immediate adoption of soil testing, but large subsidies are needed to induce 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 and/or low soil fertility but high variability in soil quality and/or 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 reports the effects of ignoring the possibility of stepwise adoption on the required cost-share subsidies for immediate adoption. The findings identify 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 sequential decision making, which offers different subsidy rates for soil testing and VRT, modeling SSCM as a package underestimates the required subsidy for adoption of VRT while it overestimates the required subsidy for soil testing.

Conclusions

A model was developed in this study 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 sequentially. Application of the model to site-specific crop management reveals the extent to which recognition of option values and the possibility of piecemeal adoption can influence forecasts about adoption. In our simulation, the model designed to account for uncertainty using the option-value approach and sequential adoption provides a better explanation for the low observed rates and sequential pattern of adoption of SSCM than models based on the NPV rule. The model also yields more precise policy implications concerning green subsidies.

Based on our results, the NPV rule predicts farmers would 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 adopt soil testing but to delay investment in VRT or not to adopt VRT at all unless the average soil quality is high and the variability in soil quality and soil fertility is relatively high. Thus the NPV rule would overpredict the adoption of VRT. Recognizing the option value of investment but ignoring the potential for stepwise adoption would tend to underpredict the adoption of soil testing and overpredict the adoption of VRT.

Our findings reveal higher reduction in nitrogen pollution with adoption of SSCM on the high average quality and fertility soils with relatively high variability. The option-value method, while considering the possibility of stepwise adoption, indicates that although a cost-share subsidy is not necessary to induce adoption of soil testing, a subsidy is needed to induce adoption of VRT, particularly on soil conditions with low average soil quality and/or fertility. Cost-share subsidies to accelerate the adoption of VRT would be most effective at reducing nitrogen pollution if targeted toward fields with low average soil quality and/or low average soil fertility 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.

We have focused only on the impacts of output price uncertainty on adoption of two interrelated technologies. Stochastic output prices are not the only source of uncertainty faced by farmers when making a decision about whether and when to invest in a new technology. Other sources of uncertainty include measurement error in soil testing and variable application, and uncertainty about revenue, costs, and weather. The inclusion of measurement error is likely to reduce the returns from site-specific technologies, as shown by Babcock, Carriquiry, and Stern in the case of soil testing. The results presented here may therefore underestimate the incentives to delay adoption. More definitive results could be achieved by extending this model to examine the full range of uncertainties, a more complete set of technical options, and a broader range of farm characteristics. Conducting the empirical analysis for numerous other randomly realized paths of output prices and finding the expected time of adoption could provide more accurate forecasts of the likely timing of adoption on each of the soil distributions.

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