Sequential Adoption of Site-Specific Technologies and its Implications for Nitrogen Productivity: A Double Selectivity Model

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Growing farm sizes are increasingly limiting the ability of farmers to manage spatial variability in their field by observation and experience. Recent developments in the state of the art technology are, however, making it possible for farmers to obtain spatially referenced data about nutrient content and soil quality in the fields and to undertake site-specific crop management and "farm by the inch." This has the potential to improve the uptake of applied inputs by plants and the efficiency of input-use. This could lead to economic benefits if gains in profits due to improved input productivity are able to more than offset the costs of adoption. It may also lead to environmental benefits to the extent that higher efficiency would reduce nitrogen residues in the soil, thereby reducing run-off and leaching of nitrates to the environment

Site-specific crop management is a bundle or package of component technologies. Two key components of this package are diagnostic techniques and application techniques. Diagnostic techniques such as soil tests and plant tissue tests are methods of detecting and analyzing spatial variability in soil nutrients at an appropriate sub-field level. Application techniques, such as a variable rate technology (VRT), implement site-specific input application decisions using computer controlled devices that vary input applications on-the-go using soil maps.

While many agricultural technologies (integrated pest management, and sustainable agricultural practices) are a package of interrelated components, farmers often adopt pieces of the package rather than the whole and adoption occurs in a sequential or step-wise manner (Byerlee and Polanco; Mann). Components of site-specific crop management are also not sold on the shelf as an integrated package and farmers have a choice in the components that they assemble. Soil testing is a prerequisite for adopting VRT but does not necessarily have to be followed by it. Farmers that adopt soil testing have the option of adjusting fertilizer application rates manually at the sub-field level or using VRT to spatially vary them on-the-go.

Estimating the impact of adoption for each of the sub-groups of adopters and non-adopters of one or both component technologies separately could lead to a ‘self-selection” bias. This bias arises because farmers endogenously self select themselves into these sub-groups and observed and unobserved characteristics of farmers may influence both their self-selection into adopters and non-adopters and the productivity enhancing outcome of that decision.

This paper has a two-fold purpose. First, it extends the existing literature by developing an empirical model to analyze the factors that influence the adoption of inter-related technologies for site-specific crop management while recognizing that this decision is sequential. Second, it examines the implications of adoption and the pattern of adoption for nitrogen productivity. Since the adoption of two component technologies is being considered here, a double selectivity econometric model is developed to control for self-selection bias. This methodology is applied to survey data for farmers in four Midwestern states of Illinois, Iowa, Indiana and Wisconsin.

Previous Research

There is limited research examining the factors that influence adoption of more than one inter-related technology (see surveys in Feder and Umali; Feder et al). Feder considers two complementary technologies and shows analytically that differences in returns to scale, risk aversion and credit constraints are important in explaining choice between the technologies and their non-adoption as an integrated package. Leathers and Smale analytically show that it is rational for imperfectly informed farmers that are uncertain about the impact of new technologies on their farm to undertake sequential adoption. Most empirical studies focus either on identifying the specific factors explaining the adoption of individual components within a package while treating their adoption as independent of other components (Thomas et.al.; Harper et al.; McNamara, et al.; Fernandez-Cornejo, and Fuglie and Bosch) or on explaining the adoption of the package as a whole (Rahm and Huffman, D’Souza et al., and Daberkow and McBride). Operationally in each case, independently defined univariate logit or probit models are used to examine the adoption decision for each component. This leads to biased and inconsistent parameters of a single equation model because the same omitted variables may influence adoption decisions for all inter-related components, leading to correlation in the error terms of equations explaining adoption decisions. The possibility that the decision to adopt a particular component may be conditional on the adoption of another complementary component is also ignored. On the other hand, single equation models examining the adoption of the bundle as a whole disregard the possibility that the same exogenous factors could influence the adoption of each of the components, included within the bundle, differently. Multiple technology choices have been analyzed using multinomial logit models (Caswell and Zilberman; Zepeda), but these models require restrictive assumptions. Studies examining the implications of adopting a modern agricultural technology for input-use, yields and profits have also typically focused on a single technology (Fernandez-Cornejo, Fuglie and Bosch, and Musser et al). The approach applied by them is extended here to correct for sample selection bias due to two adoption decisions, while analyzing the implications of sequential adoption for input productivity.

Modeling Sequential Adoption of Component Technologies

Let U_o represent the benefits to the farmer from traditional management practices and U_s represent the benefits with the adoption of soil testing. The farmer decides to adopt soil testing if $U_s{*}=U_s-U_o>0$. On the basis of information acquired by soil testing the farmer then decides whether to undertake variable rate application of fertilizers. Let U_v represent his benefits from undertaking variable rate application. He will adopt VRT, if: $U_v{*}= U_v-U_s>0$.

The net benefits he derives from the *jth* technology $U_j{*}$ is a latent variable which is assumed to be a random function of observed exogenous variables Z_j and parameters g_j and is represented by: $$U_j{*}=Z_j g_j + e_j\,;\ \ j=s,v \qquad (1)$$

where e_j is distributed normally with mean zero and variance one. The observable choices are:

$I_s=1$ if $U_s{*}>0$; $I_s=0$, otherwise. (2)

$I_v=1$ if $U_v{*}>0$ and $I_s=1$, $I_v=0$, otherwise (3)

When the random factors influencing the two adoption decisions are not independent because of unobserved factors that could affect both adoption decisions then $Cov(e_s,\ e_v)=r$. In this case, the residuals of (2) and (3) have a bivariate normal distribution and these equations should then be estimated using a bivariate probit procedure (Hausman and Wise, Tunali, Amemiya). This procedure needs to be modified to take into account the sequential rather than joint nature of the adoption process. If both the adoption decisions in (2) and (3) were defined over the entire set of observations, then a joint (simultaneous) decision model with a four way classification of farmers into the following groups would result: $(I_s=1,I_v=1)$, $(I_s=1,I_v=0)$, $(I_s=0,I_v=1)$, $(I_s=0,I_v=0)$. However, since selection equation (3) is defined only over the sub-sample where $I_s=1$, it leads to a bivariate sequential decision model with a three way grouping of farmers. Identification of the parameters in the two selection equations in (2) and (3) requires the imposition of one restriction on the matrices of explanatory variables of these two equations.

A Double Selectivity Model

Let $Y= f(X)$ represent reduced forms of the relationship between an endogenous variable such as yield per unit nitrogen and a vector of exogenous variables $\boldsymbol{X}$. This relationship is expected to vary with the technology adoption decision such that

$Y_{sv}=Xb_{sv}+h_{sv}$ if $I_s=1,I_v=1$ (4)

$Y_{so}=Xb_{so}+h_{so}$ if $I_s=1,I_v=0$ (5)

$Y_{oo}=Xb_{oo}+h_{oo}$ if $I_s=0$ (6)

The residuals e_s and e_v could be correlated not only with each other (when $r\ ^{1}0$) but also correlated with each of the residuals, h_{sv}, h_{so} and h_{oo}, leading to selectivity bias and inconsistent estimates of the parameters of equations (4)-(6). Lee's two stage consistent method for correcting single selectivity is extended to obtain the following with $r\ ^{1}0$:

$$Y_{sv} = \mathrm{X}b_{\mathrm{sv}} + s^{s}_{sv}\hat{l}^{s}_{sv} + s^{v}_{sv}\hat{l}^{v}_{sv} + x_{sv} \quad \text{if} \quad I_s = 1, I_v = 1 \qquad (7)$$

$$Y_{so} = \mathrm{X}b_{so} + s^{s}_{so}\hat{l}^{s}_{so} + s^{v}_{so}\hat{l}^{v}_{so} + x_{so} \quad \text{if} \quad I_s = 1, I_v = 0 \qquad (8)$$

$$Y_{00} = \mathrm{X}b_{00} + s^{s}_{oo}\hat{l}^{s}_{oo} + x_{00} \quad \text{if} \quad I_s = 0 \qquad (9)$$

The lambdas are the double selection analogs of the inverse Mill's ratio that arise in the context of single-selection. These equations are estimated using two-stage least squares. A procedure for obtaining consistent estimates of these standard errors in the double selectivity case is developed by Tunali. Equations (7)-(9) are then used to examine the expected change in *Y* due to the adoption of VRT and soil testing as compared to the non-adoption of both by a farmer while keeping his unobserved characteristics unchanged:

$$E(Y_{sv} \mid I_s = 1, I_v = 1) - E(Y_{oo} \mid I_s = 1, I_v = 1) = \mathrm{X}(\hat{b}_{\mathrm{sv}} - \hat{b}_{\mathrm{oo}}) + (\hat{s}^{s}_{sv} - \hat{s}^{s}_{oo})\hat{l}^{s}_{sv} + \hat{s}^{v}_{sv}\hat{l}^{v}_{sv} \qquad (10)$$

Similarly, the expected potential change in *Y* that farmers that adopted only soil testing would have experienced if they had also adopted VRT is given by:

$$E(Y_{sv} \mid I_s = 1, I_v = 0) - E(Y_{so} \mid I_s = 1, I_v = 0) = \mathrm{X}(\hat{b}_{sv} - \hat{b}_{so}) + (\hat{s}^{s}_{sv} - \hat{s}^{s}_{so})l^{s}_{so} + (\hat{s}^{v}_{sv} - \hat{s}^{v}_{so})l^{v}_{vo} \qquad (11)$$

Data

The data for this study was collected through a mail survey of 1000 randomly selected cash grain farmers located in four Midwestern states, Iowa, Illinois, Indiana and Wisconsin, in 1997. There were 650 usable responses. Of these respondents, 40 percent are from Illinois, 32 percent from Iowa, 16 percent from Indiana and 12 percent from Wisconsin. Survey participants were asked about their adoption decisions in 1996 for one or more tests for soil fertility (SOILTEST) and for VRT for fertilizer application. Of the 650 farmers, 81 had adopted both VRT and SOILTEST, 324 had adopted only SOILTEST and 245 had adopted neither.

The variables used in this study to explain adoption and the implications of adoption for nitrogen use include proxies for scale economies, human capital, innovativeness, land ownership, relative soil quality, costs of adoption and location. The effect of scale of operation is proxied by cropped acres. The availability of human capital is indicated by education level and years of farming experience. Innovativeness and technical ability are proxied by the use of new practices such as forward contracts to sell the crop (as in McNamara et al.; Fernandez-Cornejo) and by the years of use of a computer for farm business. Soil quality is proxied by a measure of relative productivity, defined as the ratio of historical corn yield per acre of the farm to the average historical county yield per acre. Since a majority of the farmers were relying on professional dealers for providing soil testing and input application services, distance of the farm from the nearest professional service provider is used as a proxy for the ease of adoption of these technologies. A dummy variable equal to one if farmers indicated that they would be willing to adopt if a cost-share subsidy of up to 20 percent was provided is used to examine the disincentives for adoption due to its high costs. The inclusion of this ‘cost’ variable in the selection equation for VRT only satisfies the condition for identification. The effects of farm location are also captured by creating regional dummies for the four states covered in the survey.

Results

The estimated parameters (Table 1) show that the null hypothesis that the covariance parameter r is zero is rejected at the 1% level, indicating the validity of estimating the two selection equations jointly. A positive value for r indicates that unobserved factors that influenced the adoption of soil testing also increased the likelihood of adopting VRT. The model predicted 46% of the adopters of VRT correctly and 85% of the non-adopters of VRT correctly. It predicted 62% of the adopters of soil tests correctly and 61% of the non-adopters correctly.

A major factor influencing the adoption of soil tests is farm location, proximity to professional dealers that provide soil-testing services. The state in which the farm is located also has a statistically significant impact on the probability of adoption of soil testing. Farmers in Wisconsin, Iowa and Indiana were significantly more likely to undertake soil testing than farmers in Illinois. The number of acres cropped has an insignificant impact on adoption of soil testing, supporting the hypothesis that soil testing is scale neutral. Innovativeness and availability of human capital do not appear to have significantly influenced the decision to adopt soil testing. With soil tests becoming a relatively commonplace technology, adoption was not restricted to the more innovative farmers or those possessing greater human capital. In contrast, the early adopters of the new and technically more sophisticated VRT were the larger, college-educated, experienced and innovative farmers. They were more technically competent and able to spread the costs of learning and information acquisition over a larger number of acres.

Farmers with relatively higher soil quality were significantly more likely to adopt VRT. Since nitrogen application rates are typically determined by the potential yield of the soil (Illinois Agronomy Handbook), nitrogen use per acre and input costs per acre are likely to be higher on relatively higher quality soils. Thus cost savings from more precise input applications and from even relatively small gains in productivity could be greater on the relatively higher quality soils, making such farms more likely to adopt VRT. Proximity of the farm to fertilizer dealers and state-wise location of farms also plays a significant role in influencing adoption of VRT. While farmers in Illinois were less likely to undertake soil testing as compared to the other states, they were more likely to adopt VRT relative to farmers in Wisconsin. The differential impact of the same explanatory variables such as state-wise location and human capital on the adoption of soil testing and VRT indicates the importance of treating these components as inter-related but distinct from each other and not defining an adopter as one who had adopted any one of these two components (as in Daberkow and McBride). The cost of adoption of VRT was a barrier to adoption and provision of a cost share subsidy would significantly increase adoption. Owners were less likely to adopt VRT as compared to those leasing the land (as in Fuglie and Bosch in the case of soil testing), perhaps due to greater risk aversion among them.

Determinants of Input Productivity

Results of the double selectivity model (Table 2) indicate that for farmers that did not adopt either soil testing or VRT, nitrogen productivity (measured by the ratio of corn yield per unit of nitrogen applied to corn) decreased significantly as crop acreage increased. An increase in farm size unaccompanied by appropriate data collection and analysis is likely to be accompanied with declining amount of agronomic information per acre. Nitrogen productivity was also lower for full time operators than for part time operators. This could reflect over application of fertilizers by them, in the presence of uncertainty about input-productivity, due to greater risk aversion among them as compared to part time operators that may have other sources of income. Farmers, however, do appear to reduce nitrogen applications to credit for the application of organic fertilizers, those using manure achieved statistically significantly higher yield per unit nitrogen applied. Non-adopters with higher than average soil quality and with college education were able to achieve higher nitrogen productivity than other farmers.

With the adoption of soil testing and VRT, availability of human capital continues to be important in determining the ability of farmers to use these technologies appropriately to make better decisions and realize the benefits of adoption. Gains in nitrogen productivity are higher for full time operators, because adoption of soil testing reduces uncertainty about required application rates and therefore risk aversion may no longer have led to over-application of nitrogen. This could also be because full time operators were more likely to have the time to analyze and utilize the information generated by these technologies. Farmers that apply manure and therefore face greater uncertainty about soil requirements for commercial fertilizer also achieve higher productivity of nitrogen after adoption. Farmers that adopted one or both components were able to offset the effects of soil quality by substituting better information about soil conditions, so that soil quality no longer has a significant impact on nitrogen productivity.

The coefficients of the selectivity correction variables for the adopters of one or both components are all significant, indicating that self-selection occurred in adoption. Estimated coefficients show that non-adopters of soil tests had higher than average nitrogen productivity as compared to adopters since l^s for the non-adopters (in (9)) of soil tests is by definition negative.

Implications of Sequential Adoption of Site-Specific Technologies for Nitrogen Productivity

The effects of adoption on nitrogen productivity are determined for a representative farm with three alternative levels of relative soil productivity (Table 3). It shows that although the probability of adoption of both components was higher on farms with relatively higher soil quality, gains in nitrogen productivity with the adoption of both components were higher on relatively lower quality soils. For a representative farmer that adopted both soil testing and VRT, average productivity of nitrogen increased by 0.34 on farms with below average soil quality and by 0.23 on farms with average soil quality. This increase was statistically significant only on farms with average and below average soil quality. The impact on the average productivity of nitrogen on farms with above average soil quality was positive but insignificant. For farmers that adopted both components, it was the adoption of VRT that led to the largest increase in nitrogen productivity. The gains in nitrogen productivity from adopting soil testing were statistically insignificant and only 0.05 and 0.06 for the below average and average soil qualities, while the additional gains from adopting VRT on these farms were 0.29 and 0.17 respectively.

To examine the rationality of the decision made by farmers, who only adopted soil testing and decided not to adopt VRT, we examined the impact of adoption of only soil testing relative to non-adoption by these farmers. A counter-factual comparison of the implications for productivity for these farms if they had adopted VRT is also conducted. Results show that farms that adopted only soil testing realized much larger gains from adopting soil testing (0.27 on the low quality soils and 0.21 on the high quality soils) and would have realized much smaller additional gains if they had adopted VRT. These potential additional gains from adopting VRT for these farmers were much smaller than the gains realized by farmers that did adopt VRT. These differential gains in adoption for the two groups of farmers (those that adopted only soil testing and those that adopted both) arise due to differences in their selectivity variables which in turn could reflect differences in unobserved characteristics such as extent of spatial variability on their fields. Adoption of VRT is likely to have a greater profitability advantage over conventional farming methods on fields where there is greater spatial variability in soil conditions. It is possible that farmers that adopted only soil testing had low levels of spatial variability on their fields and learning about the levels of soil fertility was sufficient to improve decision making about input application rates and profits. Additional gains in input productivity and net profits that may have resulted from the spatially varying input application rates by adopting VRT may not have justified incurring the costs of adopting it.

Conclusions

This paper shows that while ease of adoption and state-wise location were important in influencing the adoption of soil testing, it was the more technically competent, educated farmers and those able to spread the costs of learning and information acquisition over a larger number of acres that were more likely to adopt both soil testing and VRT. Although the probability of adoption of both technologies was higher on farms with relatively higher soil quality, gains in nitrogen productivity are found to be higher on farms with relatively lower quality. For farms that adopted both soil testing and VRT, most of these gains were achieved by the adoption of VRT. A counter-factual comparison shows that farms that adopted soil testing only achieved much larger gains in nitrogen productivity due to the adoption of soil testing alone as compared to farmers that adopted both components. The potential additional gains from adopting VRT for these farmers was much smaller than the gains realized by farmers that actually did adopt VRT.

Table 1:Determinants of the Probability of Adoption

	Bivariate		**Marginal Effects**	
	Soil Test	**VRT**	**Soil Test**	**Both Soil Test and VRT**
CONSTANT	-0.3201 (0.4569)	-2.98 (0.647)		
ACRES	0.0001 (0.0001)	0.0003 (0.0001)*	0.000006 (0.000008)	0.000003 (.000001)***
COLLEGE	0.062 (0.117)	0.3 (0.155)**	-0.058 (0.075)	0.019 (0.012)*
EXPERIENCE	0.0041 (0.005)	0.014 (0.008)*	0.0011 (0.0033)	0.0014 (0.0007)**
COMPUTER	0.0115 (0.0125)	0.043 (0.017)**	0.0028 (0.008)	0.0044 (0.0017)***
CONTRACT	0.205 (0.119)*	0.471 (0.145)***	0.074 (0.07)	0.0547 (0.0153)***
COST		-0.453 (0.255)*	0.0367	-0.037 (0.017)**
MANURE	-0.092 (0.111)	-0.109 (0.147)	-0.0048 (0.071)	-0.016 (0.015)
OWN	0.17 (0.181)	-0.549 (0.278)**	0.138 (0.117)	-0.0307 (0.027)*
OPERATOR	-0.244 (0.234)	-0.416 (0.322)	-0.130 (0.15)	-0.023 (0.032)
SOIL QUALITY	0.413 (0.30)*	1.117 (0.424)***	0.136 (0.195)	0.124 (0.042)***
DISTANCE	-0.0125 (0.005)**	-0.025 (0.01)***	-0.005 (0.003)*	-0.003 (0.0009)***
WISC	0.462 (0.185)***	-0.982 (0.396)**	0.332 (0.119)**	-0.042 (0.026)*
IOWA	0.611 (0.132)***	-0.058 (0.175)	0.339 (0.089)***	0.045 (0.034)
INDIANA	0.293 (0.155)*	-0.230 (0.212)	0.179 (0.099)*	0.005 (0.019)
RHO	0.9 (0.36)***			
Correctly predicted adopters of:	Soil Tests and VRT: 37/81 Soil Tests only: 275/324 Neither: 155/244			
N	650	405		
Log Likelihood	-572.61			
χ^2[1]	0.03{0}	0.001{0}		

Standard errors are in parenthesis. Degrees of freedom are in square brackets. P-value is in curly brackets. χ^2[1] is the Wu-Hausman test for exogeneity of the variable computer. *** Statistically significant at the 1% level; ** Statistically significant at a 5% level; *Statistically significant at a 10 % level (two-tailed tests).

Table 3: Determinants of Nitrogen Productivity

	Yield per unit Nitrogen (bushels of corn per pound of nitrogen)		
	Non-adopters	Adopters of Soil Tests only	Adopters of Soil Test and VRT
CONSTANT	0.758 (0.138)***	1.15 (0.27)***	0.186 (1.41)
ACRES	-.00007 (0.00003)**	-0.000053 (0.00007)	0.00003 (0.12)
COLLEGE	0.054 (0.032)*	0.065 (0.0.035)*	0.171 (0.08)**
EXPERIENCE	0.0009 (0.0015)	0.0002 (0.003)	0.0054 (0.007)
COMPUTER	-0.004 (0.0035)	-0.0042 (0.0091)	0.0075 (0.021)
CONTRACT	0.011 (0.037)	0.0032 (0.084)	0.061 (0.23)
MANURE	0.056 (0.032)*	0.10 (0.06)*	0.050 (0.14)
OPERATOR	-0.11 (0.065)*	0.085 (0.05)*	0.053 (0.31)
OWN	0.022 (0.054)	0.008 (0.087)	-0.036 (0.39)
SOIL QUALITY	0.082 (0.046)*	0.066 (0.19)	0.092 (0.47)
λ^v		-0.15 (0.098)*	0.229 (0.12)*
λ^s	-0.19 (0.077)**	-0.37 (0.20)*	0.632 (0.35)*
N	245	324	81
R^2	9.3%	11%	10.8%
F[K, N-K-1]	2.4{0.009}	3.6{0.0001}	3.5{0}

Notes: Standard errors are in parenthesis. Degrees of freedom are in square brackets. P-value is in curly brackets. F[K, N-K-1] is a F-test for all slope coefficients jointly equal to zero with K=number of explanatory variables.

Table 3: Implications of Adoption for Nitrogen Productivity

Implications for Yield Per Unit Nitrogen of an Adopter of Both Technologies			
	Low Soil Quality	Average Soil Quality	High Soil Quality
Probability of adoption			
Soil Tests Only	0.49	0.51	0.45
Both Soil Tests and VRT	0.03	0.097	0.23
With neither soil tests or VRT	0.82	0.86	0.89
With Soil Tests only	0.87	0.92	0.95
With Soil Tests and VRT	1.16	1.09	1.03
Change due to adoption of Soil Tests	0.05	0.06	0.06
Total Change due to adoption of Soil Tests and VRT	0.34**	0.23*	0.13
Implications for Yield Per Unit Nitrogen of an Adopter of Soil Tests Only			
With neither soil tests or VRT	0.66	0.71	0.75
With Soil Tests only	0.93	0.95	0.96
With Soil Tests and VRT	1.11	1.08	1.07
Change due to Adoption of Soil Tests	0.27**	0.24**	0.21*
Additional change if VRT had been adopted	0.17	0.13	0.12

Low, average and high quality soils are defined as Soil Quality=0.5, 1 and 1.5 respectively. Other characteristics of the representative farmer considered here are Acres=1000, Contract=1, Operator=0, Owner=0, Experience=10, Computer=5, College=1, Manure=1, Distance=10, Cost=1, Illinois=1.

*** Statistically significant at the 1% level; ** Statistically significant at the 5% level; * Statistically significant at the 10 % level (all two-tailed tests).

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