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Information and the Adoption of Precision Farming Technologies

William D. McBride and Stan G. Daberkow

Precision farming technologies have been commercially available since the early 1990s, but the pace of adoption among U.S. farmers has been modest. This study examines the relationship between the adoption of diagnostic and application techniques of precision farming and sources of information available to farmers about precision farming. The model used in the analysis accounts for sources of self-selection in the adoption process that could bias the results. Results indicate interpersonal information sources have increased adoption relative to information from the mass media, and the private sector has been the driving force behind the diffusion of precision farming. Information from crop consultants and input suppliers has had the greatest impact on the adoption of precision farming technologies. These sources likely provide the greatest technical expertise about precision farming, and thus are better equipped to ease the significant human capital requirement of precision farming technologies.

Key Words: information sources, logit analysis, precision farming, self-selection bias, technology adoption

Precision farming (PF) technologies for site-specific crop management offer a way to manage the sub-field variability of soils, pests, landscapes, and microclimates by spatially adjusting input use to maximize profits and potentially reduce environmental risks. These technologies involve geo-referencing, which allows producers to micro-manage soil and plant processes within small areas of a single field. PF technologies have been commercially available since the early 1990s. However, not only has the pace of adoption in the United States been relatively modest, but a large number of farmers are apparently not familiar with these technologies. A 1998 nationwide survey of over 8,400 U.S. farms indicated nearly 70% of farmers were not aware of PF technologies, while less than 5% had adopted some aspect of PF. The vast majority of those unaware of PF technologies were among the smallest farm operations (Daberkow and McBride, 2000).

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Technology transfer, broadly defined, involves the conveying of information to potential users about the technology, and has traditionally fallen under the purview of the Cooperative Extension Service and other areas within the public-sector system. However, the growth of private-sector innovations and the strengthening of intellectual property rights over the last 20 years have had important implications for technology transfer. The private sector has become increasingly important relative to the public sector in the delivery of agricultural technology, as expenditures in agribusiness marketing budgets have increased while federal expenditures for public extension have declined (National Research Council, 2001). Private-sector vendors logically seek to work with farm operators who can contribute the most to their profits, and so they are more likely to seek out larger farm operations and develop products that make it easier to manage larger farms. This practice has raised concerns about the structural implications of the expanding role of the private sector in agricultural technology diffusion.

Public policy issues have surfaced about the potential impact of PF adoption on farm structure (Pierce and Nowak, 1999; National Research Council, 1997, 2001). Questions have been raised concerning (*a*) the level of public funding of PF research, education, and extension activities, and (*b*) appropriate public-private roles in assisting producers in gaining access to PF technologies (Cowan, 2000). An understanding of how public and private institutions have influenced the adoption of PF technologies is needed to address these questions.

The general objective of this study is to identify the factors associated with PF adoption among U.S. farmers. More specifically, we seek to provide insights about how farmers' perceptions and attitudes are influenced by different sources of PF information, and the effects these "agents of change" are having on PF adoption.

Background

The technology adoption literature often alludes to different stages in the adoption process and the role played by information in each stage. Beale and Bolen (1955) were among the first to synthesize research suggesting awareness is the critical first stage of the agricultural technology diffusion process.[1] They defined awareness as the stage where an individual learns of the existence of a technology or practice but has little knowledge about it. Most individuals were thought to become aware of new ideas through the mass communications media. In a 1986 study of early adopters and non-users of farming technology, Carlson and Dillman found that different sources of information become important at different stages of adoption. In agreement with this finding, Kromm and White (1991) conclude the media are important in the early awareness stage; neighbors, crop consultants, and agricultural professionals provide input during the testing and evaluation stage; and personal experience is critical during the adoption, intensification, and/or retention stage.

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[1] The awareness stage was hypothesized by Beale and Bolen (1955) to be followed sequentially by the interest, evaluation, trial, and adoption stages.

Rollins (1993) found most potential adopters of new technology rely on several information sources, and preferred information sources change during the various stages of adoption. Hence, he suggests certain information sources can be "more effective change agents" than others and different information sources can influence the probability of adoption. Similarly, research by Rogers (1995) and Korsching and Hoban (1990) indicates different sources of information are influential during different stages of the adoption process—with mass media (i.e., radio, newspapers, television, and magazines) most important during the initial stages, and information about the specific technology critical in the latter stages.

Longo (1990) separates the delivery of information to potential adopters into two distinct categories: (*a*) mass media, and (*b*) interpersonal communication (e.g., crop consultants, extension agents, demonstrations, input suppliers, other growers, etc.). She tested the traditional assumption that the mass media is important in creating awareness of the existence of agricultural innovations (but such information sources seldom led to adoption), whereas interpersonal communication, which typically involves contacts in face-to-face situations, is the basic means of transferring more technical (and adoption-promoting) information. While Longo notes the effects of mass media and interpersonal communication are likely interrelated, she cites several studies where no relationship was found between mass media and interpersonal communication relative to subsequent agricultural technology adoption. However, Longo found that in Brazil, mass media channels were more important in explaining the adoption of cropping innovations than the interpersonal channels of communication.

Based on the results of several adoption studies, perceptions and attitudes about emerging technologies are also influenced by different sources of information. In an empirical analysis, Adesina and Zinnah (1993) found farmers' perceptions about the characteristics of rice varieties affected the adoption decision. Similarly, Lynne, Shonkwiler, and Rola (1988) concluded that farmers' attitudes about conservation influenced their adoption of soil conservation practices. McBride, Daberkow, and Christensen (1999) reported producer attitudes about PF were influenced by different information sources, with crop consultants more influential than media sources. In their study of integrated pest management adoption practices, Thomas, Ladewig, and McIntosh (1990) found information from personal contacts was most likely to influence attitudes about adoption. Moreover, as noted by Feather and Amacher (1994), producer perceptions play an important role in the adoption decision, and providing information to producers can change their perceptions by reducing uncertainty about the technology.

The nature of the agricultural technology or practice, in combination with farm and operator characteristics, also interacts with information sources to influence adoption. For example, Saltier, Bauder, and Palakovich (1994) found access to information plays a stronger role in the adoption of management-intensive practices (among which PF technologies seem to fit) than it does for low-input methods. Feder and Slade (1984) noted farm size influences both the access to information and the adoption decision.

Rather than rely on passive forms of information, some studies have suggested producers may actively seek information about innovations, and the effort to gain information about a technology is directly related to the expected gain from that knowledge (Feder and Slade, 1984; Feder, Just, and Zilberman, 1985). Information about the profitability of new technologies, however, often is not readily available during the early adoption stages. In the case of precision farming, information related to the economic benefits and costs of complete systems or of individual components has only recently become available (Lambert and Lowenberg-DeBoer, 2000).

In summary, information appears to influence adoption via several pathways, and different sources of information are expected to be more influential during each phase of the adoption process. Information disseminated by the mass media appears to be the most common channel through which farmers are made aware of the existence of an innovation. Interpersonal information sources, such as vendors and other growers, have a greater impact on the attitudes and perceptions about an innovation. Finally, technical (or "how-to") information from sources such as vendors and professional consultants is shown to be most important to the potential adopter.

Empirical Framework

Incomplete information diffusion has important implications for the empirical analysis of technology adoption. Much of the applied adoption research has used a probit or logit analysis of survey data to identify the probability of adoption given socioeconomic and other characteristics of adopters and nonadopters. Many of these studies assumed the entire population under study was aware of the technology being examined (e.g., Adesina and Zinnah, 1993; Gould, Saupe, and Klemme, 1989; Norris and Batie, 1987). Based on this awareness and other factors, producers made a choice whether or not to adopt the technology. However, PF techniques are relatively recent, complex innovations of which many farmers are not aware, and those aware are not likely to represent a random sample of all farm operators. This presents the problem of self-selection. If the self-selection problem is left uncorrected, results from the analysis of adoption could be biased.

The adoption of precision farming for site-specific crop management involves a choice among component technologies, including both diagnostic techniques and application techniques (Khanna, 2001). Diagnostic techniques are methods of gathering data and analyzing spatial variability at the sub-field level, including such technologies as yield monitors, and soil and plant attribute sensors. Application techniques implement site-specific input application decisions using computer-controlled devices which vary input applications as machines move across the field.

Farmers have a choice in the components they adopt, but diagnostic techniques must be used to determine the spatial variability in yields, nutrient requirements, and/or pest pressures, before variable-rate application techniques can be effective. However, farmers can use diagnostic techniques and not employ variable-rate application techniques. For example, yield monitors or soil sampling could reveal homogeneous conditions across a field, suggesting that uniform rather than variable-rate input application is more appropriate.

PF adoption is therefore a sequential process involving the use of diagnostic techniques for data gathering which may or may not lead to the use of variable-rate input applications. Consequently, farmers aware of PF techniques self-select themselves into a group through their adoption/nonadoption decisions, instead of being randomly selected from the survey respondents. The sequential nature of PF adoption is another source of self-selection that could bias the results.

To develop the empirical framework for addressing these issues, consider that a farmer becomes aware of PF technologies when the acquired information level crosses a certain threshold:

$$I(\mathbf{d}) - I_0 > 0, \tag{1}$$

where the acquired information level I depends on $\mathbf{d}$, a vector containing the farmer's relevant economic and demographic variables, and I_0 is the information threshold level. For the purpose of estimation, the awareness (w) of PF technologies in (1) can be expressed as:

$$y_w = \mathbf{X}_w \boldsymbol{\beta}_w + \varepsilon_w, \tag{2}$$

where $\mathbf{X}_w$ is a matrix containing the farmer's economic and demographic variables which influence the acquired information level, $\boldsymbol{\beta}_w$ is a vector of parameters to be estimated, and ε_w is an error term. $I(\mathbf{d})$ and I_0 in (1) are not observable. What is observed is the farmer's response to the question of whether or not he/she is aware of PF technologies. Therefore, y_w is denoted as an indicator of awareness which equals 1 if the farmer is aware of PF technologies [i.e., $I(\mathbf{d}) - I_0 > 0$], and zero otherwise.

Once a farmer is aware of PF technologies, the farmer then chooses to adopt a PF technology if the perceived adoption benefit exceeds the adoption costs. Because of the sequential process by which PF diagnostic and application techniques are adopted, the PF adoption decision can be expressed in two parts. The first decision of whether or not to adopt a diagnostic technique, conditional on awareness of PF technologies, can be expressed as:

$$y_{d|w} = \mathbf{X}_d \boldsymbol{\beta}_d + \mathbf{Z}\boldsymbol{\delta} + \varepsilon_d, \tag{3}$$

whereas the decision to adopt an application technique, conditional on the adoption of a diagnostic technique, is specified as:

$$y_{a|wd} = \mathbf{X}_a \boldsymbol{\beta}_a + \mathbf{Z}\boldsymbol{\delta} + \varepsilon_a, \tag{4}$$

where $\mathbf{X}_d$ and $\mathbf{X}_a$ are matrices of regressors containing the producer's economic and demographic variables which influence adoption, $\boldsymbol{\beta}_d$ and $\boldsymbol{\beta}_a$ are vectors of parameters to be estimated, and ε_d and ε_a are error terms. **Z** is a matrix of regressors containing the producer's source of information about PF technologies, and **δ** represents the vector of associated parameters to be estimated. For estimation, $y_{d|w}$ is denoted by a binary variable equal to 1 if the producer uses a PF diagnostic technique, and zero otherwise; similarly, $y_{a|wd}$ is denoted by a binary variable equal to 1 if the producer uses an application technique, and zero otherwise. The inclusion of PF information sources in (3) and (4) allows for testing the hypothesis that differences in information sources influence the net benefits from adoption, and thus the adoption decision.

Although the model to be estimated is given in (2), (3), and (4), the issue of self-selection has yet to be addressed. First consider the decision to adopt a PF diagnostic technique. The decision to adopt a diagnostic technique is conditional on the awareness of PF. In terms of the estimation equations, this means $y_d = 1$ only if $y_w = 1$. Assuming the error terms in (2) and (3) are jointly distributed as bivariate normal, i.e., $(\varepsilon_w, \varepsilon_d) \sim \text{BNV}(0, 0, 1, 1, \rho)$ and $\rho = \text{cov}(\varepsilon_w, \varepsilon_d)$, the conditional probability of adoption is given by:

$$(5) \qquad \text{prob}(y_d = 1 | y_w = 1) = \text{E}[y_d | (I(\mathbf{d}) - I_0) > 0] = \Phi(\mathbf{X}_d \boldsymbol{\beta}_d + \mathbf{Z}\boldsymbol{\delta}) + \rho\lambda_w(\alpha_w),$$

where $\alpha_w = -\mathbf{X}_w \boldsymbol{\beta}_w$, $\lambda_w = \phi(\alpha)/1 - \Phi(\alpha)$, and Φ and ϕ denote the cumulative distribution function (cdf) and probability density function (pdf) of a univariate normal distribution, respectively.

Equation (5) suggests that direct estimation of (3) would lead to an omitted variable bias because the last term on the right-hand side of (5) would be omitted. This problem is overcome by augmenting (3) such that:

$$(6) \qquad y_{d|w} = \mathbf{X}_d \boldsymbol{\beta}_d + \mathbf{Z}\boldsymbol{\delta} + \lambda_w \theta_w + \varepsilon_d,$$

where λ_w is estimated from the results of (2), and θ_w is the parameter to be estimated.

The next step is to reflect the sequential nature of PF adoption. The decision to adopt an application technique is conditional first on the awareness of PF, and then on the adoption of a diagnostic technique. This means $y_a = 1$ only if $y_w = 1$ and $y_d = 1$. Thus, the conditional probability of adopting an application technique can be expressed as:

$$(7) \qquad \text{prob}(y_a = 1 | y_w = 1, y_d = 1) = \Phi(\mathbf{X}_a \boldsymbol{\beta}_a + \mathbf{Z}\boldsymbol{\delta}) + \rho\lambda_w(\alpha_w) + \rho\lambda_d(\alpha_d),$$

and the problem of self-selection is addressed by augmenting (4) such that:

$$(8) \qquad y_{a|wd} = \mathbf{X}_a \boldsymbol{\beta}_a + \mathbf{Z}\boldsymbol{\delta} + \lambda_w \theta_w + \lambda_d \theta_d + \varepsilon_a,$$

where λ_d is estimated from the results of (6), and θ_d is an additional parameter to be estimated. Thus, the model to be estimated is given by (2), (6), and (8). This framework for modeling technology adoption is conceptually similar to the approach used by Saha, Love, and Schwart (1994), and Klotz, Saha, and Butler (1995).

Data

Data for the analysis come from the U.S. Department of Agriculture's (USDA's) 1998 Agricultural Resource Management Survey (ARMS). Each farm sampled in the ARMS represents a known number of farms with similar attributes so that weighting the data for each farm by the number of farms it represents provides a basis for calculating estimates for the U.S. farm population. The definition of a farm, and thus the target population of the ARMS, is any business that produced $1,000 worth of agricultural production during the calendar year. The analysis assesses the adoption of PF technologies for site-specific crop management on the population of U.S. corn and soybean producers. Corn and soybean farms are defined as those harvesting one or more acres of corn or soybeans during 1998.

The ARMS collected data to measure the financial condition and characteristics of farm businesses and farm households. The PF component of the ARMS was structured to elicit information from farmers about their awareness of PF techniques, sources of information about PF, and adoption of various PF technologies. Farmers were asked whether or not they were aware of PF techniques.[2] Respondents who reported awareness of PF technologies were asked about their primary source of PF information. These farmers were also asked about their use of various PF technologies for crop production in 1998. Farmers were considered to have adopted a PF diagnostic technique if the use of either grid soil sampling, yield monitoring, or remote sensing was reported. Farmers were assumed to have adopted a PF application technique if fertilizer, pesticide, or seed was applied at variable rates.

Respondents to the ARMS survey included nearly 3,200 corn and soybean producers (table 1). About 40% of the farmers indicated they were not aware of PF technologies. Among these farmers, 29% produced less than $10,000 worth of agricultural products in 1998, while more than 77% produced less than $40,000. As seen from panel B of table 1, roughly 19% of farmers aware of precision farming had adopted a PF diagnostic technique. About 15% of these farmers produced $250,000 or more in agriculture products during 1998, compared to only 6% of those who were aware of PF but had not adopted a PF technology. Only 9% of the farmers aware of PF reported using a variable-rate application technique.

Model Specification and Estimation

The model specified in this study is estimated with a multi-stage logit approach. PF awareness is modeled in the first stage and the results are used to correct for potential self-selection bias in a second-stage adoption equation of PF diagnostic techniques. The results of both the first and second stages are then used to correct for potential self-selection bias in a third-stage adoption equation of PF application techniques.

[2] The specific question was phrased as follows: "Precision farming techniques are relatively new innovations in production agriculture. Are you aware of various precision farming techniques?"

Table 1. Distribution of the ARMS Sample of Corn and Soybean Farms, and the Distribution of Farms by Production Value, 1998

A. ALL FARMS (N = 3,193)

Description	Not Aware of Precision Farming	All Farms Aware of Precision Farming	Total
Sample N	1,025	2,168	3,193
% of Farms	41	59	100
% by Production Value:			
Less than $10,000	29	13	20
$10,000 to $39,999	48	35	41
$40,000 to $99,999	15	29	23
$100,000 to $249,999	5	16	11
$250,000 or more	3	7	5

B. FARMS AWARE OF PRECISION FARMING (N = 2,168)

Description	Precision Farming Not Adopted	Adopted Diagnostic Technique [a]	Adopted Application Technique [b]
Sample N	1,664	504	268
% of Farms	81	19	9
% by Production Value:			
Less than $10,000	13	14	0
$10,000 to $39,999	38	23	24
$40,000 to $99,999	29	25	30
$100,000 to $249,999	14	23	28
$250,000 or more	6	15	18

Notes: Corn and soybean farms were defined as operations producing at least $1,000 worth of agricultural products and harvesting one or more acres of corn or soybeans in 1998. Percentages of farms are computed using the survey weights.

[a] Diagnostic techniques included any one of the following: grid soil sampling, yield monitoring, or remote sensing.

[b] Application techniques included variable-rate applications of either fertilizer, pesticide, or seed. Adoption of application techniques is conditional on the adoption of a diagnostic technique.

Of primary interest is how changes in the various information source variables affect the adoption of PF technologies. These information sources include the extension service, crop consultants, input suppliers, special events/project demonstrations, other growers/grower associations, and the news media.

The dependent variable of the first-stage equation was specified as binary, equal to 1 if the farmer was aware of PF techniques, and zero otherwise. Only the sample farmers aware of PF were included in the second stage. The dependent variable of the second-stage equation was also a binary variable, equal to 1 if the farmer used a PF diagnostic technique, and zero otherwise. Likewise, the third-stage equation included only the farmers who had adopted a diagnostic technique, and the dependent variable was 1 if the farmer used an application technique, zero otherwise.

Independent variables included farm and operator variables (table 2). Farm size was measured as the total harvested crop acres (*CROPAC*), and was specified with a quadratic term (*CROPAC2*) [see Fernandez-Cornejo, Daberkow, and McBride (2001) for a discussion of the size effect on PF adoption]. Specialization in corn and soybean production was specified as the percentage of harvested crop acreage in corn and soybeans (*SPECIAL*). The importance of livestock to the farm operation was indicated by the percentage of farm product value from livestock products (*LSTOCK*). Operator age was measured in years (*OPAGE*).[3] Operator education was defined as the number of years of formal education including high school, college, and any post-graduate work (*OPEDUC*).

The major occupation of the operator was specified with binary variables for retired (*RETIRED*) and off-farm employment (*OFOCUP*), based on a self-assessment by the survey respondent. Respondents reporting farming as their major occupation (*FMOCUP*) was the omitted group; thus estimates for the other occupations indicate differences from the primary occupation of farming.

Use of a related or complementary technology was indicated by the use of computer records for farm income and expense accounting, measured as a binary variable (*COMPREC*). A regional identifier was included to account for spatial variation in the diffusion of PF and availability of PF vendors. The Heartland was used to identify the major corn and soybean region, and thus the region where PF vendors would be most likely to concentrate (*HLAND*).[4]

Measures of risk management, credit availability, and land tenure were included in the adoption equation for PF diagnostic techniques. A risk management score (*RISKMAN*) was developed from a series of 10 self-assessment questions about risk management practices to determine if producers who more actively managed risk would be more likely to adopt PF techniques (Bard and Barry, 1998). A variable indicating maximum borrowing capacity (*CREDCAP*) was included to examine whether the capital investment required for PF technologies posed a significant barrier to adoption (Ryan, 1999). Also included was a measure of land tenure as the percentage of operated acreage that was owned (*OWNEDAC*) to determine if the site-specific information obtained from PF technologies was more important to land-owners than to tenants.

These variables were not added to the adoption equation for PF application techniques because they were believed to have an important influence on initial adoption but not later adoption.[5] For example, diagnostic techniques require the major capital investment for PF, while variable-rate input applications can be performed by custom operators. Likewise, once PF diagnostic techniques have been performed on a field,

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[3] A quadratic term for operator age was also tried in the model, but was not statistically significant in any of the equations.

[4] The Heartland includes all of Iowa, Illinois, and Indiana, and portions of Minnesota, South Dakota, Nebraska, Missouri, Kentucky, and Ohio (Heimlich, 2002).

[5] Exclusion of these variables also ensures identification of the parameters of equation (8) and reduces the degree of collinearity among the variables.

Table 2. Description and Mean Values of Variables Used in the Precision Farming Adoption Model for Corn and Soybean Farms, 1998

		All Farms	
Variable	Description	Not Aware of Precision Farming	Aware of Precision Farming
Farm and Operator Variables:			
CROPAC	harvested crop acres (100s of acres)	2.5	5.4
SPECIAL	percent corn or soy acres specialization (%)	59	67
LSTOCK	percent product value from livestock (%)	48	32
OPAGE	operator age (years)	52	49
OPEDUC	operator's formal education (years)	12	13
FMOCUP	major occupation is farming (%)	54	68
RETIRED	operator is retired (%)	7	2
OFOCUP	major occupation is off-farm employment (%)	39	29
HLAND	farm located in Heartland region (%)	47	59
COMPREC	use of computer record-keeping technology (%)	6	19
RISKMAN	risk management (score) [c]	31	32
CREDCAP	maximum borrowing capacity ($1,000s)	166	261
OWNEDAC	percent of acres owned (%)	54	36
PF Information Source Variables:			
EXTSVS	extension service (% of farms)	NA	12
CROPCON	crop consultants (% of farms)	NA	5
INPSUPP	input suppliers (% of farms)	NA	25
DEMO	special events/demonstrations (% of farms)	NA	3
GROWERS	other growers/grower associations (% of farms)	NA	7
MMEDIA	mass media sources[d] (% of farms)	NA	47

Notes: Corn and soybean farms were defined as operations producing at least $1,000 worth of agricultural products and harvesting one or more acres of corn or soybeans in 1998. Mean values are computed using the survey weights. NA = not applicable.

[a] Diagnostic techniques included any one of the following: grid soil sampling, yield monitoring, or remote sensing.

[b] Application techniques included variable-rate applications of either fertilizer, pesticide, or seed. Adoption of application techniques is conditional on the adoption of a diagnostic technique.

[c] Higher risk management scores are associated with producers who more actively manage risk.

[d] Mass media sources include print and electronic media sources, such as newsletters, trade magazines, television, radio, and the internet.

the tenure of the field is not likely to influence the decision to apply inputs at variable rates.

The major source of information about precision farming was specified as a series of binary variables in the adoption equations. These variables indicate the major PF information source as the extension service (*EXTSVS*), crop consultants (*CROPCON*), input suppliers (*INPSUPP*), special events/demonstration projects (*DEMO*), or other growers/grower associations (*GROWERS*). Mass media sources (*MMEDIA*) were omitted during estimation to determine the impact of various inter-

Table 2. Extended

	Farms Aware of Precision Farming		
Variable	Precision Farming Not Adopted	Adopted Diagnostic Technique [a]	Adopted Application Technique [b]
Farm and Operator Variables:			
CROPAC	4.9	7.9	9.2
SPECIAL	63	80	82
LSTOCK	35	25	24
OPAGE	49	48	47
OPEDUC	13	14	14
FMOCUP	68	69	79
RETIRED	2	2	1
OFOCUP	29	30	20
HLAND	55	77	78
COMPREC	16	37	26
RISKMAN	32	33	34
CREDCAP	249	314	331
OWNEDAC	37	33	28
PF Information Source Variables:			
EXTSVS	11	17	7
CROPCON	4	10	16
INPSUPP	23	38	54
DEMO	3	3	3
GROWERS	7	6	3
MMEDIA	52	25	18

personal information sources on adoption, relative to the impact of information obtained via the media.[6] Among farmers who were aware of PF but had not adopted any PF technologies, 52% indicated the mass media was their major source of PF information, compared to only 25% of farmers adopting a PF diagnostic technique (table 2). These findings are supported by results of other studies (Carlson and Dillman, 1986; Kromm and White, 1991; Rogers, 1995; Korsching and Hoban, 1990) where the mass media was found to be the major source of technology awareness, but interpersonal information sources were observed to have a more important role in technology adoption.

The model indicated by equations (2), (6), and (8) was estimated using Heckman's (1979) multi-stage approach. Parameters of each equation were estimated using the ARMS survey weights in a weighted least squares version of the maximum-

[6] The mass media includes print and electronic media, such as newsletters, trade magazines, television, radio, and the internet.

likelihood method. Due to the complex design of the ARMS sample, standard errors were estimated using a jackknife replication approach (Dubman, 2000).[7]

Results

The multivariate logit regression model is useful for simultaneously assessing the impacts of specific variables on the probability of a farm operator belonging to a given group, while accounting for the impact of other variables. Human capital attributes of the farm operator, size and specialization of the operation, operator occupation, and use of a complementary technology were found to have a statistically significant effect on the probability of being aware of PF technologies (table 3). Operator age was not statistically significant, but greater education and the use of a computer record-keeping system for farm financial management were significant, and both increased the likelihood of PF awareness.

Retired farm operators and operators whose major occupation was off-farm employment were less likely to be aware of PF technologies. Operators dependent on farming as the primary income source and those with a greater investment in human capital tend to seek out information on new farming techniques and are thus more likely to be exposed to PF technologies. Increasing farm size led to a greater likelihood of PF awareness, with the probability increasing at a decreasing rate. Specialization in corn and soybean production also increased the likelihood that the farm operator was aware of PF technologies. More crop acreage and greater specialization in corn and soybeans are likely to enhance the information exposure to site-specific crop management technologies because these technologies would likely be marketed to larger farms, and most have applications to corn and soybean production.

The second stage of the analysis examined the PF adoption decision of a diagnostic technique, given that a farm operator was aware of PF (table 3). Farm size, specialization of the operation, and computer familiarity were statistically significant and found to positively affect the probability of adoption. Increasing farm size increased the probability of adoption at a decreasing rate. These results are consistent with previous PF adoption research where farm size and use of computer records increased the likelihood of adoption (Daberkow and McBride, 2000).

Increasing operator age was found to decrease the likelihood of PF adoption, while greater education made adoption more likely. Younger farm operators have a longer planning horizon, and education likely enhances the skills required for experimenting with PF technologies. Location in the Heartland, the leading corn and soybean production region, increased the probability of PF adoption. This could be due to the presence of more PF vendors in the area. Also, the likelihood of PF adoption increased with the proportion of acreage owned. Information collected with PF

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[7] Parameters estimated with Heckman's multi-stage approach are consistent, but not as efficient as those estimated with the maximum-likelihood approach. However, Heckman's method was used in this study because of its computational simplicity, and because of the difficulties in obtaining convergence with the maximum-likelihood method for each of the jackknife replicates.

Table 3. Regression Results of the Precision Farming Adoption Model for Corn and Soybean Farms, 1998

	Aware of Precision Farming Technologies		Adopted Diagnostic Technique[a]		Adopted Application Technique[b]	
Variable	Parameter	Std. Error	Parameter	Std. Error	Parameter	Std. Error
Intercept	!2.33059*	1.30233	!5.93020**	1.37507	!8.35476**	3.31595
CROPAC	0.12395**	0.02341	0.14222**	0.04998	0.12831*	0.06359
CROPAC2	!0.00146**	0.00050	!0.00131**	0.00053	!0.00133*	0.00088
SPECIAL	0.01181**	0.00392	0.01929**	0.00531	0.02001**	0.00897
LSTOCK	!0.00008	0.00342	!0.00362*	0.00200	!0.00232	0.00168
OPAGE	!0.01211	0.00763	!0.02070*	0.00973	!0.01909*	0.00940
OPEDUC	0.16115**	0.06345	0.10944**	0.03689	0.08437*	0.04501
RETIRED[c]	!0.68526*	0.37762	!0.02891	0.02164	!0.61614	0.38245
OFOCUP[c]	!0.42389*	0.22667	!0.10856	0.07334	0.29196	0.18089
HLAND	0.24043	0.20097	0.92659**	0.36887	0.94711**	0.42851
COMPREC	0.90771*	0.43306	1.42654**	0.46776	0.63696	0.40803
RISKMAN	—	—	0.01263	0.00858	—	—
CREDCAP	—	—	!0.00004	0.00003	—	—
OWNEDAC	—	—	0.00911*	0.00441	—	—
EXTSVS[d]	—	—	0.64496*	0.36364	1.23708*	0.60807
CROPCON[d]	—	—	1.76083**	0.26957	3.27329**	0.98333
INPSUPP[d]	—	—	1.19877**	0.24049	2.46018**	0.86713
DEMO[d]	—	—	0.61273*	0.31661	0.41341	0.27789
GROWERS[d]	—	—	0.53991*	0.26226	!0.08302	0.06212
λ_w	—	—	!0.55676*	0.26319	0.29169	0.19779
λ_d	—	—	—	—	!2.24628*	1.05033
Samples w/attribute	2,168		504		268	
Samples w/o attribute	1,025		1,664		236	
Total samples	3,193		2,168		504	
Likelihood ratio[e]	100,942 (d.f.=10)		62,150 (d.f.=19)		14,678 (d.f.=17)	
McFadden's R^2	0.13		0.20		0.18	
Predicted correct	71%		83%		71%	

Notes: Single and double asterisks (*) denote significance at the 10% and 5% levels, respectively. Using the jackknife variance estimator with 15 replicates means the critical *t*-values are 2.145 at the 5% level, and 1.761 at the 10% level.
[a] Diagnostic techniques included any one of the following: grid soil sampling, yield monitoring, or remote sensing.
[b] Application techniques included variable-rate applications of either fertilizer, pesticide, or seed. Adoption of application techniques is conditional on the adoption of a diagnostic technique.
[c] Coefficient interpreted relative to the deleted group, farming occupation (*FMOCUP*).
[d] Coefficient interpreted relative to the deleted group, mass media (*MMEDIA*).
[e] The likelihood ratio is distributed as a χ^2 statistic to test the null hypothesis that all coefficients except the intercept are equal to zero. The null hypothesis is rejected for all models.

diagnostic techniques is site-specific and long-term in nature, and thus is likely to be more valuable to the landowner than to the tenant-farmer. Previous research (see Feder, Just, and Zilberman, 1985) identified risk attitudes and capital availability as factors influencing technology adoption, but these factors were not statistically significant in this analysis.

PF information sources were included to assess the relative importance of various sources to the PF adoption decision. The variable identifying the mass media as the primary PF information source was the deleted group in the estimation. Therefore, the coefficients on the other information sources indicate differences from the mass media. For example, the significant and positive coefficient on the extension service variable indicates that farmers who used the extension service as their primary PF information source were more likely to adopt PF technologies than farmers with the mass media as their primary source of information (table 3). Obtaining the major source of PF information from all the interpersonal sources specified in the model increased the likelihood (relative to information from the mass media) a producer would adopt a diagnostic technique of PF.

In the third stage of the analysis, adoption of a PF application technique was examined, given that a farm operator had adopted a diagnostic technique (table 3). Farm size, specialization of the operation, and operator age and education were statistically significant in the model. Based on these results, among farmers who had already adopted a PF diagnostic technique, the adoption of an application technique was more likely among the larger and more specialized operations, and among the younger and more educated. Location in the Heartland, the leading corn and soybean production region, was found to increase the probability of adopting a PF application technique. PF information sources also had a statistically significant impact on the adoption of an application technique. Obtaining the major source of PF information from the extension service, crop consultants, and input suppliers increased the likelihood (relative to information from the mass media) a producer would adopt an application technique of PF.[8]

The change in the probability of adopting precision farming technologies associated with each of the explanatory variables is shown in table 4. Among the farm and operator variables, the probability of adopting a diagnostic technique declines by 0.0025, or 0.25%, for each year of operator age. This means the probability of adoption by a 40-year-old farm operator is about 2.5% higher than that of a 50-year-old operator. Adoption probabilities increased with each year of operator education, about 1.3% for diagnostic techniques and 1.6% for application techniques. Farm location in the Heartland region and the use of computer records in the farm business had a substantial impact, raising the likelihood of adoption by 11% and 17%, respectively, for diagnostic techniques, and 18% and 12% for application techniques.

Impact of the various information sources on the probability of adoption is also shown in table 4. The change in the probability of PF adoption from each information source indicates the impact each had relative to information from the mass media. For example, the probability of adopting a diagnostic technique goes up by 0.086, or about 9%, when the extension service provides the major source of PF information compared to the mass media. Information from crop consultants had the largest impact on the adoption of PF diagnostic techniques, increasing the adoption prob-

[8] The coefficients on selectivity correction variables were also statistically significant in both adoption equations, indicating self-selection had occurred.

Table 4. Change in the Probability of Adopting Precision Farming Technologies Associated with Each Variable, 1998

	Change in Probability of Adopting:			Change in Probability of Adopting:	
Variable	Diagnostic Technique[a]	Application Technique[b]	Variable	Diagnostic Technique[a]	Application Technique[b]
Farm and Operator Variables:			**PF Information Source Variables:**[c]		
CROPAC	0.01713	0.02476	*EXTSVS*	0.08588	0.21322
CROPAC2	!0.00016	!0.00026	*CROPCON*	0.27676	0.49686
SPECIAL	0.00232	0.00386	*INPSUPP*	0.15975	0.46877
LSTOCK	!0.00044	!0.00045	*DEMO*	0.08266	0.07924
OPAGE	!0.00249	!0.00368	*GROWERS*	0.07123	!0.01604
OPEDUC	0.01318	0.01628			
RETIRED	!0.00348	!0.11890			
OFOCUP	!0.01307	0.05634			
HLAND	0.11157	0.18277			
COMPREC	0.17177	0.12292			
RISKMAN	0.00152	—			
CREDCAP	!0.00001	—			
OWNEDAC	0.00110	—			

[a] Diagnostic techniques included any one of the following: grid soil sampling, yield monitoring, or remote sensing.
[b] Application techniques included variable-rate applications of either fertilizer, pesticide, or seed. Adoption of application techniques is conditional on the adoption of a diagnostic technique.
[c] Change in the mean precision farming adoption probability compared to the mass media (*MMEDIA*) being the primary source of precision farming information.

ability by about 28%. Information from input suppliers increased the adoption probability of diagnostic techniques by 16%, while the extension service, product demonstrations, and other growers or grower associations each had an impact of less than 10%.

Information from crop consultants and input suppliers had a substantial impact on the adoption of application techniques (conditional on the use of a diagnostic technique), increasing the adoption probability by nearly 50% for both information sources. Contact with the extension service increased the likelihood of a variable-rate input application by more than 20%, but information from other sources did not have an impact statistically different from that of media sources.

Conclusions

Precision farming techniques are relatively new technologies that typically require a significant investment in human capital and currently have an uncertain payoff. Hence, it is not surprising this study found farm operator attributes, including operator age, education, and familiarity with computers, to be particularly important in explaining PF adoption. These human capital traits were important to the adoption of a PF diagnostic technique and, among those who had adopted a diagnostic technique, operator age and education influenced the adoption of a variable-rate application technique.

Further, this study did not find financial capital to be limiting to PF adoption. A growing service sector for PF technologies suggests custom operators can be used to provide PF methods, limiting the financial capital requirement. However, the significant human capital investment likely makes PF more attractive to larger and specialized operations where this investment can be spread over more units of production. In addition, PF technologies may have been marketed more aggressively to these larger operations because of the greater profit potential for PF vendors.

While farmers utilized a variety of information sources about precision farming, certain sources had relatively more influence on the adoption decision for both diagnostic and application techniques. Results suggest PF adoption has been driven primarily by private-sector agents. Commercial crop consultants appear to be the agents having the greatest influence on both stages of PF adoption. Crop consultants are specialists who most likely have the greatest technical expertise about PF, and thus are better able to ease the human capital burden confronted by farmers.

Input suppliers have also impacted adoption to a much greater extent than have other agents, particularly for variable-rate applications. Input suppliers have an incentive to provide support services for the inputs they supply (e.g., seed, fertilizer, pesticides). PF services may be seen as a method for developing a closer and longer-term relationship with customers. By contrast, the extension service and grower associations deal with a wide variety of issues affecting crop producers. This lack of specialization in issues addressed by PF indicates they may not provide the same level of technical support as the other agents, and thus have had less of an impact on adoption.

An implication from the role played by information sources in the adoption of PF technologies is that personalized technical support, such as expertise provided by crop consultants and input suppliers, appears to have the greatest impact on adoption. This effect is most apparent in the decision to adopt application techniques where adoption probabilities increase by nearly 50% when the primary information source is crop consultants or input providers. Programs providing personalized technical assistance would likely be the most effective strategy for promoting PF adoption. This type of technical support would be much more expensive to provide than generic information programs, but could be administered through cost-sharing or other incentives which encourage farmers to utilize private-sector sources of PF expertise. A program of this type could improve access to PF techniques for farmers not currently targeted by private-sector sources of PF information and technical support.

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