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Adoption and Abandonment of Precision Soil Sampling in Cotton Production

Jonathan C. Walton, Dayton M. Lambert, Roland K. Roberts, James A. Larson, Burton C. English, Sherry L. Larkin, Steven W. Martin, Michele C. Marra, Kenneth W. Paxton, and Jeanne M. Reeves

Adoption of precision agriculture technology has received considerable attention, but abandonment has received little. This paper identifies factors motivating adoption and abandonment of precision soil sampling in cotton. Younger producers who farmed more cotton area, owned more of their cropland, planted more non-cotton area, or used a computer were more likely to adopt precision soil sampling. Those with more cotton area or who owned livestock were more likely to abandon, while those who used precision soil sampling longer, or used variable-rate fertilizer application were less likely to abandon precision soil sampling.

Key words: abandonment, adoption, cotton, precision agriculture, soil sampling, Southeastern United States

Introduction

Precision farming technologies include information technologies and variable-rate application technologies. Factors influencing adoption and abandonment change as new technologies are developed, and research is needed to understand and keep pace with this evolution. An extensive body of research explains which farm and farmer characteristics are associated with the adoption of agronomic decision-making technologies (e.g., Feder and Slade, 1984; Putler and Zilberman, 1988; Batte, Jones, and Schnitkey, 1990; Amponsah, 1995; Daberkow and McBride, 2003).

Producers adopt new agricultural technologies based on the expected economic benefits gained from the technology. Yet, reasons producers abandon such technologies have received less attention. Once a technology is adopted, the producer may abandon the technology if the benefits produced by the technology are perceived to be less than cost of continued use. Rogers (1983) refers to this type of technology abandonment as "disenchantment discontinuance." Like other agricultural technologies, some precision agriculture technologies are discarded in favor of newer, more efficient technologies. Rogers categorizes these decisions as "replacement discontinuance."

Jonathan C. Walton is graduate research assistant, Dayton M. Lambert is assistant professor, Roland K. Roberts is professor, James A. Larson is associate professor, and Burton C. English is professor, all in the Department of Agricultural Economics, The University of Tennessee, Knoxville; Sherry L. Larkin is associate professor, Department of Food and Resource Economics, University of Florida, Gainesville; Steven W. Martin is associate professor, Delta Research and Extension Center, Stoneville, Mississippi; Michele C. Marra is professor, Department of Agricultural and Resource Economics, North Carolina State University, Raleigh; Kenneth W. Paxton is professor, Department of Agricultural Economics and Agribusiness, Louisiana State University, Baton Rouge; and Jeanne M. Reeves is Director of Agricultural Research, Cotton, Inc., Cary, North Carolina.
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Previous research (e.g., Khanna, 2001; Roberts et al., 2004) examined the relationship between site-specific information gathered using soil testing technology and adoption of variable-rate application of inputs in agriculture. Other research has evaluated how the use of variable-rate technology influences the value, and consequently the adoption, of site-specific information (Bullock, Lowenberg-DeBoer, and Swinton, 2002). The relationship between the information-gathering and other precision farming activities, such as variable-rate application, makes information technology a logical starting point for investigating technology adoption and abandonment.

Carletto, de Janvry, and Sadoulet (1996) looked at adoption and subsequent abandonment of hormone use in dairy cattle and export crops, respectively. Their research provides an opening for analyzing why some precision agriculture technologies are abandoned. Foltz and Chang (2002) and Barham et al. (2004) studied the adoption of recombinant bovine somatotropin (rBST), and examined the characteristics of farmers who abandoned that technology. Barham et al. found that abandonment decisions were moderated in cases where adoption of a given technology involved significant sunk costs. The results of the rBST adoption study found no differences between the characteristics of adopters and those who stopped using the technology. An important parallel between rBST and soil sampling technologies is that they both have low sunk costs associated with adoption. Grid and management zone soil sampling only have variable costs that depend on the acres sampled and sampling intensity (Swinton and Jones, 1998).

Precision agricultural technologies are generally more profitable with high-valued crops, such as cotton (Swinton and Lowenberg-DeBoer, 1998). The typical entry point for grain producers interested in precision farming technology has been through the installation of electronic yield monitors on harvesting equipment (Lowenberg-DeBoer, 1999). Farmers typically use monitors to observe yield differences in fields and follow up with other information technologies such as precision soil sampling.

Cotton growers are equally as passionate about yields as grain farmers are, but the adoption sequence of precision farming technology in cotton production has differed because of the lack of reliable yield monitoring technologies. Reliable yield monitors for cotton were not available until 2000, while monitors for grains and oilseeds have been on the market since the early 1990s (Perry et al., 2001). Thus, the typical entry point into precision farming for cotton producers has been through the adoption of grid or management zone soil sampling (precision soil sampling), not yield monitoring.

A 2001 survey of cotton producers in six southern states indicated that only 3% of 1,373 survey respondents used cotton yield monitors compared with 41% using precision soil sampling (Roberts et al., 2002). Users of grid soil sampling at the time of the 2001 survey reported an average of 8.4 years of experience with the technology. Thus, precision soil sampling is a relatively widely adopted and mature precision farming technology for which cotton farmers have had sufficient time to evaluate its benefits and costs.

The objective of this research was to determine the farm and farmer characteristics influencing the adoption and subsequent abandonment of precision soil sampling by cotton producers. Specifically, we focus on the adoption and subsequent abandonment of precision soil sampling by cotton producers in 11 Southeastern states (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, Missouri, North Carolina, South Carolina, Tennessee, and Virginia). Current use of precision soil sampling in these states provides sufficient information to assess abandonment of the technology.

This article seeks to fill part of the gap in the literature on the abandonment of precision farming technologies in crop production. Identification of the factors influencing farmers who choose to either continue using or abandon precision soil sampling may provide insight into why certain agricultural technologies succeed or fail in the marketplace. Knowledge of the characteristics associated with abandonment provides a more in-depth understanding of the adoption process. This information could assist agribusiness with the development and upgrading of technologies to better suit the needs of end-users. In addition, an understanding of why farmers abandon such practices might provide Extension insight with respect to training or other kinds of information dissemination to encourage producers to continue using these practices in environmentally sensitive habitats (Lambert et al., 2007).

Conceptual Model for Adoption and Abandonment of Precision Soil Sampling

Reasons for abandoning precision soil sampling falling under the rubric of "disenchantment discontinuance" include (*a*) there is a lack of field variability; (*b*) current management practices may be consistent with prescriptive results; (*c*) the information is difficult or too costly to apply; or (*d*) the producer may be easing out of production (e.g., lifestyle changes).

First, when crop response to inputs is homogeneous across a field (Bullock, Lowenberg-DeBoer, and Swinton, 2002), and/or the expected benefits from fertilizer carryover and crop uptake dynamics approach zero (Lambert, Lowenberg-DeBoer, and Malzer, 2007), variable rate input application is less likely to be profitable and might be the impetus for abandoning precision soil sampling.

Second, given farmer experience and familiarity with field history, precision soil sampling may indicate that the producers' current input management practices are consistent with the soil sample prescription (Lambert, Lowenberg-DeBoer, and Malzer, 2006). In these cases, farmers may purchase precision soil sampling information only to find that they are already managing inputs optimally for that field.

Third, site-specific information may be difficult to interpret and convert into a useful management plan (Griffin and Lambert, 2005). Or, the costs of implementing a management plan based on soil test information may outweigh the expected benefits of hiring custom variable-rate services, purchasing new variable-rate equipment, learning how to apply variable-rate inputs based on a management plan, or retrofitting older equipment for variable-rate input application (Swinton and Lowenberg-DeBoer, 1998; Bullock, Lowenberg-DeBoer, and Swinton, 2002).

Fourth, producer planning horizons may influence adoption of some information-gathering technologies (Lambert et al., 2007). For some producers, minimizing the time spent farming may be more important than maximizing farm profits (Nehring, Fernandez-Cornejo, and Banker, 2002). Concerns over farm succession (Wilson, 1997; Battershill and Gilg, 1997), the desire to reduce the time and energy spent farming (Lobley and Potter, 1998), or the need for income stability (Loftus and Kraft, 2003) may also affect technology adoption or abandonment.

Finally, producers who adopted precision soil sampling may abandon it if an alternative technology provides similar information at a lower cost [i.e., Roger's (1983) "replacement discontinuance"]. For example, automated soil pH sensors (Adamchuk, Morgan, and Lowenberg-DeBoer, 2004) or soil electroconductivity information or other sensor information (Adamchuck et al., 2004) may be more cost-effective for gathering some kinds of soil fertility information compared to grid or zone precision soil sampling.

Adoption and Abandonment Decisions

Just as there are a variety of reasons a producer would adopt precision soil sampling, there are numerous reasons a farmer would abandon the technology for cotton or for other crops. For the utility-maximizing producer, the adopt/abandon decision is a tradeoff between the prior and realized expected utility of adopting and then applying precision soil sampling information. The decision to adopt a particular technology occurs only once, but the decision to continue using that technology is updated as the difference between the prior expected net present benefits calculated before adoption and the realized net present benefits observed in a subsequent period after adoption. However, like adoption, the decision to abandon a particular technology is also a one-time event. Therefore, the adoption decision is considered the point at which the farmer purchased precision soil information. That information may be used to augment input management plans and may be useful for several years (Swinton and Lowenberg-DeBoer, 1998), and then possibly purchased again. Or, for various reasons, the purchased information may never be used—i.e., it is immediately abandoned.

Cotton producers are rational agents who face a discrete choice to adopt precision soil sampling (PSS) at time t_0. The producer maximizes the discounted expected benefits from cotton, grain crops, and/or livestock production over a time horizon, and therefore weighs the costs of incorporating a new technology into his or her management portfolio. Let $E[U(\pi_{t_0}^{PSS})]$ ($E[U(\pi_{t_0})]$) be the expected utility of profit (π) from adopting (rejecting) precision soil sampling technology in period t_0. In the initial period, the differences in profit amount to the quasi-fixed costs associated with grid or zone soil sampling, the additional costs associated with implementing a management plan based on the soil test results, and the change in yield due to implementation of the management plan (Bullock, Swinton, and Lowenberg-DeBoer, 2002). Defining $U_{AD}^{*} = E[U_{AD}(\pi_{t_0}^{PSS})] - E[U_{NA}(\pi_{t_0})]$, the utility-maximizing producer adopts precision soil sampling when $U_{AD}^{*} > 0$ (Khanna, 2001; Roberts et al., 2004).

Considering the abandonment decision, let $U(\pi_t \mid U_{AD}^{*} > 0)$ represent the utility from ex post profits t production periods after adopting precision soil sampling, and $E[U(\pi_t \mid U_{AD}^{*} > 0)]$ the ex ante utility from profit in period t, given adoption of precision soil sampling. Defining $U_{AB}^{*} = U(\pi_t \mid U_{AD}^{*} > 0) - E[U(\pi_t \mid U_{AD}^{*} > 0)]$, the utility-maximizing producer abandons precision soil sampling when $U_{AB}^{*} < 0$, or when the utility from realized profit is lower than the expected utility from profit in period t, given adoption of precision soil sampling.

This simple model assumes the decision maker is myopic; abandonment happens immediately following disappointing profits. In some cases, it may be that the farmer continues using soil test information for some period, attributing losses to other factors. The model also assumes that adoption and abandonment are one-time events. A producer may discontinue using the technology, only to return to the technology at a later date or a different field. The model also assumes that profit in period t is adjusted for the costs associated with precision soil sampling. The costs of grid and zone soil sampling and maps made from its information are "quasi-fixed" costs, but the costs of managing the information per se are probably negligible, assuming easy storage of maps or other site-specific information. However, the costs of implementing a management plan based on the soil sampling information (e.g., variable-rate input application) may be substantial. The abandonment decision therefore considers the (discounted) start-up costs of soil sampling and management decision aids (e.g., maps), and the change in variable costs due to executing management plans based on this information.

By choosing to adopt precision soil sampling, the producer self-selects into the sample of farmers who discontinue precision soil sampling or continue to value information collected from precision soil sampling. This sequence suggests the use of econometric methods that attend to sample-selection bias (Heckman, 1976; Khanna, 2001; Roberts et al., 2004). The unobservable latent variables U_{AD}^* and U_{AB}^* are hypothesized to be random functions of observable exogenous variables (Z_{AD}, Z_{AB}) such that:

(1a)
$$U_{AD}^* = Z_{AD}A + e_{AD}$$

and

(1b)
$$U_{AB}^* = Z_{AB}B + e_{AB},$$

where (A, B) are unknown parameters and (e_{AD}, e_{AB}) are random disturbance terms. The latent variables are not directly observable, but dichotomous variables measure the producer's decisions as follows: $I_{AD} = 1$ if $U_{AD}^* > 0$ (0 otherwise), and $I_{AB} = 1$ if $U_{AB}^* \subset U_{AD}^*$ and $U_{AB}^* > 0$ (0 otherwise). It is common to assume that the variance of the error terms is equal to one as implied by the standard normal distribution because multiplication of the unobserved variables U_{AD}^* or U_{AB}^* by any positive constant does not change the interpretation of I_{AD} or I_{AB}.

With these assumptions, the indicator variables I_{AD} and I_{AB} measure the probabilities (Pr) associated with the decisions characterized by equations (1a) and (1b). The probability of abandoning following adoption is written as:

(2)
$$\Pr(I_{AB} = 1, I_{AD} = 1) = \Pr(I_{AB} = 1 \mid I_{AD} = 1) * \Pr(I_{AD} = 1) = \Phi_2(Z_{AB}A, Z_{AD}B, \rho),$$

where Φ_2 is the cumulative distribution function of the standard bivariate normal distribution, and ρ is the correlation between the random disturbances in equations (1a) and (1b). The probability of adopting but not abandoning the technology is:

(3)
$$\Pr(I_{AB} = 0, I_{AD} = 1) = \Phi(Z_{AD}A) - \Phi_2(Z_{AB}A, Z_{AD}B, \rho).$$

The probability of not adopting the technology is:

(4)
$$\Pr(I_{AD} = 0) = 1 - \Phi(Z_{AD}A) = \Phi(-Z_{AD}A).$$

The resulting sample log-likelihood objective function (L) for this system is given by (Greene, 2000):

(5)
$$\max_{A,B,\rho} \ln \mathrm{L} = \sum_{AB\in 1, AD\in 1} \ln\left[\Pr(I_{AB}=1, I_{AD}=1)\right] + \sum_{AB\in 0, AD\in 1} \ln\left[\Pr(I_{AB}=0, I_{AD}=1)\right] + \sum_{AD\in 0} \ln\left[\Pr(I_{AD}=0)\right].$$

Statistical significance of ρ suggests that the producer self-selecting into the "abandon" and "adopt" groups is systematic. Intuitively, the expected value of ρ is positive and should be close to one; a producer abandoning the technology must have been an adopter. When there is no sample selection bias (e.g., $\rho = 0$), the adoption and abandonment models can be estimated as separate probit regressions, noting that the group discontinuing the use of the technology is a subset of the adoption group.

To facilitate interpretation of the results, the marginal effects for the adoption part of the system are $\partial \Pr(I_{AD} = 1)/\partial z_k$, for the kth explanatory variable. The marginal effects for abandonment, conditioned on adoption of the technology, are estimated as $\partial \Pr(I_{AB} = 1 \mid I_{AD} = 1)/\partial z_k$. Standard errors of the marginal effects are estimated with the delta method (Greene, 2000).

Survey Data

The data were collected from a survey of cotton producers in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, Missouri, North Carolina, South Carolina, Tennessee, and Virginia (Cochran et al., 2006). The survey questionnaires were mailed on January 28, 2005. Reminders and follow-up mailings were sent on February 4, 2005 and February 23, 2005, respectively. Of the 12,243 surveys mailed, 200 were returned either undeliverable or by farmers indicating they were no longer cotton producers. A total of 12,043 cotton farmers remained in the sample after these exclusions. Thus, the usable response rate was 10% (1,216 cotton producers).

Producers answered questions about the extent to which precision agriculture technologies were used on their farms as well as information on the general structure and characteristics of their farming operations. They were also asked about the profitability of precision agriculture in their operation as well as the outlook on the future prospects of precision farming in general. A total of 827 farmers responded to the question asking whether they had adopted precision soil sampling. Three hundred thirty-five farmers (40.5%) stated they had tried precision soil sampling and among those, 56 (16.7%) had subsequently discontinued use of precision soil sampling.

To assess how well the respondents of this study represented the population of cotton farmers in the Southeastern United States, the survey data were compared with data from the 2002 Agricultural Census [U.S. Department of Agriculture/National Agricultural Statistics Service (USDA/NASS), 2004]. The average age of the respondents (50 years) was slightly less than the average age of cotton farmers (52 years) reported in the census for the 11 states. The average cotton enterprise size calculated from the census was 635 acres for the 11 states, while the average size was 815 acres for survey respondents. The difference between the survey respondents and the census data is explained, in part, by protocols used in recording the census data. In particular, there is a need to prevent identification of farms in the larger census categories. Information on relatively larger farms is included because this study only reports statistics on aggregated data. Also, planted cotton area decreased by 650,000 acres between 2002 and 2004 in the 11 states surveyed (USDA/NASS, 2004). Thus, the survey data used here are representative of larger farms relative to the census figures. Given that larger farms have higher adoption rates for certain precision farming technologies (Daberkow and McBride, 2003), the data in this study are well suited to analyzing the population of farmers more likely to be affected by factors associated with adoption and abandonment of precision soil sampling.

Empirical Models

The empirical models for precision soil sampling adoption and abandonment were specified as:

$$ADOPT_i = A'Z_{AD,i} + e_i, \quad (6a)$$

$$ABANDON_{j\in i=1} = B'Z_{AB,j\in i=1} + e_{j\in i=1}, \quad (6b)$$

where $ADOPT = 1$ if farmer i adopted precision soil sampling (0 otherwise), and $ABANDON = 1$ if the farmer $j \in i$ abandoned precision soil sampling (0 otherwise). Descriptive statistics and definitions of producer characteristics and farm attributes (Z_{AD} and Z_{AB}), along with their expected relationships with adoption and discontinuance, are reported in table 1.

When $\rho = 0$, there is no selectivity bias and [(6a), (6b)] can be estimated as separate probit regressions; equation (6a) would be estimated using probit regression with the full sample, and equation (6b) would be estimated using probit regression with the subsample of adopters. If $\rho \neq 0$, a full-information maximum-likelihood (FIML) procedure would be used to maximize the log-likelihood function of the system [equation (5)], and standard errors would be estimated with a heteroskedastic robust covariance estimator (Greene, 2000).

Multicollinearity

Multicollinearity can affect the inferential power of tests by inflating the variance of estimates. Variance inflation factors were used to determine whether standard errors were inflated (Chatterjee and Price, 1991). Variance inflation factors greater than 10 suggest standard errors may be inflated by collinearity.

Exogeneity Tests

A common problem encountered in survey analyses is that certain attributes or characteristics of a respondent may be codetermined with the response variable. For example, use of a computer may be part of a precision technology package adopted by the producer. Yield variability may be lower for producers who use precision soil sampling because it enables them to target inputs site-specifically. Farm household income may be higher from more efficient farm management, which may be due to the technology in question. Complementary relationships between technologies and practices may also affect farmer perceptions of the expected value of a decision (Barham et al., 2004).

One approach for addressing this issue is to model the variables hypothesized to be endogenous as a system of equations with instrumental variables. A data-driven approach includes forming hypotheses about the exogeneity of the variables in question, and then statistically testing these hypotheses. We take the second approach in this study, noting that rejection of the exogeneity hypotheses suggests a more complicated two-stage instrumental variable model. In both cases, the reliability of answers to questions about the exogeneity of certain variables is limited by the number of instrumental variables available for these tests or for a complete two-stage system.

Table 1. Variable Definitions, Hypothesized Signs, and Means in the Precision Soil Sampling Adoption and Abandonment Equations

Variable	Definition	Hypothesized Sign: Adopt	Hypothesized Sign: Abandon	Mean (Std. Error)
Farmer Characteristics:				
AGE	Age in years of the primary decision maker	–	+	49.98 (11.33)
QUADAGE	Age in years squared	+	–	2,576.31 (1,145.47)
EDUC	Number of years of formal education	+	–	14.29 (2.20)
COM	= 1 if the farmer used a computer for farm management; 0 otherwise	+	–	0.58 (0.49)
EXTEN	= 1 if the farmer perceived Extension services helpful in implementing precision farming practices; 0 otherwise	+	–	0.84 (0.49)
PROFIT	= 1 if the farmer thought it would be profitable to use precision agricultural technologies in the future; 0 otherwise	+	–	0.54 (0.49)
Farm Characteristics:				
ACRES	Average cotton acreage grown in 2003 and 2004	+	–	800.34 (947.83)
OCROPS	Percentage of non-cotton acreage to total cropped acreage	+	–	23.54 (27.38)
LIVEST	= 1 if the farming operation included livestock; 0 otherwise	–	+	0.27 (0.45)
LANDTEN	Percentage of owned land to total land farmed	+	–	31.17 (31.34)
YVAR	Difference between the farmer's estimates of average yields for the most productive ⅓ of and the least productive ⅓ of a typical field	+	–	522.33 (249.07)
INCOME	= 1 if pre-tax household income was greater than $150,000; 0 otherwise	+	–	0.33 (0.47)
YRSADOPT	Number of years precision soil sampling was used		–	4.12 (8.60)
VRPKL	= 1 if variable-rate application of P, K, or L was used; 0 otherwise		–	0.20 (0.40)
Location Variables:				
ERS1	Heartland	+ / –	+ / –	0.035 (0.18)
ERS2	Eastern Uplands	+ / –	+ / –	0.052 (0.22)
ERS3	Fruitful Rim	+ / –	+ / –	0.045 (0.21)
ERS4	Mississippi Portal	+ / –	+ / –	0.365 (0.48)
ERS5	Southern Seaboard (reference region)	+ / –	+ / –	0.503 (0.50)

Variables in the adoption equation hypothesized to be potentially endogenous include cotton acreage (*ACRES*), percentage of total cropped acreage devoted to other crops (*OCROPS*), yield variability (*YVAR*), computer use in farm management (*COM*), and household income above $150,000 (*INCOME*). The same variables were hypothesized to be potentially endogenous in the abandonment equation, in addition to the number of years precision soil sampling had been used (*YRSADOPT*) and the use of variable-rate application of phosphorus, potassium, and lime (*VRPKL*).

The use of precision soil sampling could enable more efficient management of larger operations, increase managerial efficiency, or decrease yield variability. Managing data generated by precision soil sampling is likely accomplished using computer-based technology. Uncertainty regarding the issue of whether computers were used previously to make management decisions or if their use was a result of adopting an array of precision agriculture technologies is difficult to untangle. The use of precision soil sampling data has the potential to increase managerial efficiency, thereby potentially increasing profit and income reported by the producer. The decision to continue the use of precision soil sampling is also related to the number of years it was used. And finally, the use of variable-rate application may require information from precision soil sampling.

The Rivers and Vuong (1988) procedure was used to test the assumption that these variables were exogenous. Each variable whose exogeneity was questionable was regressed against all other exogenous variables, and an additional set of instrumental variables. The residuals from these regressions were then included as additional explanatory variables in a separate estimation of the adoption-abandonment system. For the binary variables hypothesized to be exogenous, the score vector proxies the residuals (Vella, 1992). The joint significance of the coefficients associated with the residual terms was tested using a Wald test (Wooldridge, 2002). Failure to reject the null hypothesis is evidence that these variables are exogenous.

The instruments for the test included all exogenous variables in the adoption equation along with additional instruments. Instrumental variables used in the Rivers-Vuong test included annual precipitation, July humidity, and January sunlight hours, all from the USDA/ERS weblink (http://www.ers.usda.gov/Data/NaturalAmenities, 2005). Additional instrumental variables included a population interaction index (a rurality measure; USDA/ERS, 2005), and variables indicating whether the county the respondent lived in was classified as a manufacturing-dependent county, low employment county, or low education county in 2003 (USDA/ERS, 2003). These instruments were selected because they were determined outside the producers' immediate decision-making framework for farm management activities [e.g., farm location, climate patterns influencing production, access to agricultural support service (as physical or human capital), off-farm work opportunities, etc.], but were correlated with variables hypothesized to be exogenous.

Comparison of characteristics between adopters ($n = 335$) and nonadopters ($n = 492$), and producers who abandoned ($n = 56$) and who continued ($n = 279$) soil sampling were made to provide further insight into the factors motivating adoption and abandonment. Hartley's F-max test (Lentner and Bishop, 1993) was used to determine if the variances of the characteristic variables from each subset were significantly different. When the null hypothesis of equal variance between the groups was rejected, degrees of freedom for the sample t-tests were adjusted using Satterthwaite's procedure (Lentner and Bishop). Farmer characteristics and farm attributes were compared at the 5% level.

Hypotheses

Six farmer characteristics were hypothesized to influence the expected utility of adopting and abandoning precision soil sampling (table 1). Farmer age (*AGE*) was expected to be negatively associated with adoption of soil sampling and positively associated with discontinuance. As age increases, the individuals' planning horizon decreases and limits the time period when farmers perceive they can make changes and offset learning costs (Batte, Jones, and Schnitkey, 1990; Roberts et al., 2004). The square of the age coefficient (*QUADAGE*) captures elements of experience. The expected utility derived from adopting precision soil sampling was hypothesized to increase with age for younger farmers as familiarity and experience with precision agricultural technologies grow, but decline after a certain age as the planning horizon shortens (Putler and Zilberman, 1988; Alexander and Van Mellor, 2005).

The number of years of formal education (*EDUC*) was anticipated to increase the expected utility from adopting precision soil sampling, but decrease the likelihood of abandoning the technology. Higher levels of formal education may increase the analytical ability of operators managing the voluminous amount of data generated by precision agriculture (Batte, Jones, and Schnitkey, 1990).

In the same way, computer use in farm management (*COM*) should relate positively with adoption but negatively with abandonment of soil sampling. Because computer technology is either integrated into precision agricultural technology or used to transfer and manage precision farming data, computer use for farm management is likely tied to adoption and abandonment decisions.

Higher income levels from farming (*INCOME*) should be positively associated with the expected utility derived from adoption of precision soil sampling, but negatively influence discontinuance. In this study, high income households were those reporting annual income from farm and off-farm sources greater than $150,000. Higher income could facilitate investment in precision farming technologies while lack of resources may increase the likelihood of abandoning soil sampling due to an inability to obtain other complementary technologies or consultation (Rogers, 1983).

Farmers who responded that Extension services were useful in making precision farming decisions (*EXTEN*) were expected to be more likely to use precision soil sampling. These same attitudes were hypothesized to negatively correlate with soil sampling abandonment. Therefore, the ability of Extension to provide useful information to farmers could reduce disenchantment discontinuance.

Positive perceptions about the future profitability of precision agriculture (*PROFIT*) were expected to be positively related to the likelihood of adopting soil sampling, and negatively associated with the probability of abandoning the technology. Farmers may be more willing to adopt and continue using precision soil sampling when they perceive future payoffs to be greater than the costs.

Seven farm characteristics were hypothesized to correlate with the likelihood of adopting and/or abandoning precision soil sampling (table 1). The number of cotton acres planted (*ACRES*) measured enterprise size, and was hypothesized to be positively related with the expected utility of adopting precision soil sampling, but negatively correlated with abandonment of the technology. Farmers who operated relatively more cotton acres were expected to be more likely to use precision soil sampling by virtue of scale economies. The percentage of total farm acres planted with other crops (*OCROPS*) was expected to be positively correlated with the adoption, but negatively related with abandonment of soil sampling. Farmers who placed greater emphasis on grain and oilseed crops may apply soil test information used for these crops to manage cotton inputs.

Enterprise diversification was measured by livestock ownership (*LIVEST*) and was expected to be negatively correlated with the adoption decision, but positively associated with the likelihood of abandoning the technology. Fernandez-Cornejo, Beach, and Huang (1994) found that livestock production had a negative impact on the adoption of integrated pest management. Management of an enterprise not directly related to precision soil sampling may reduce the time available to effectively apply soil test information.

The percentage of total acres owned (*LANDTEN*) was hypothesized to be positively correlated with the precision soil sampling adoption decision, but negatively associated with the likelihood of abandoning it. Farmers likely pay more managerial attention to land owned than rented because owned land may be passed to subsequent generations.

Yield variability (*YVAR*) was hypothesized to increase the likelihood of adopting precision soil sampling, but reduce the likelihood of abandoning the technology. Technologies increasing management and input application efficiency can increase profitability (Larson and Roberts, 2004), and the ability to manage inputs more effectively may decrease yield variability.

The number of years precision soil sampling had been used (*YRSADOPT*) was hypothesized to be negatively correlated with the decision to abandon precision soil sampling. Continued use of a technology is evidence that the technology provided some benefit to the adopter greater than the cost of its adoption. Variable-rate application of phosphorus, potassium, and lime was hypothesized to decrease the likelihood of abandoning soil sampling. The use of variable-rate application of inputs (*VRPKL*) may suggest that benefits from the adoption of precision soil sampling outweigh its costs by providing information about optimal input placement.

The USDA/ERS farm resource regions were included in the soil sampling adoption and abandonment models (table 1) (USDA/ERS, 2007). These regional variables were hypothesized to control for differences in land prices, access to farm services, climate, and growing seasons (Khanna, 2001). The Southern Seaboard (*ERS6*) region was chosen as the reference region because it had the modal number of survey responses. The hypotheses tested were whether cotton producers in the Heartland (*ERS1*), Eastern Uplands (*ERS5*), Fruitful Rim (*ERS7*), and Mississippi Portal (*ERS9*) regions were more likely to adopt or abandon precision soil sampling than cotton producers in the Southern Seaboard region.

Results and Discussion

Univariate Comparison of Adopters with Nonadopters

Cotton producers who adopted precision soil sampling were younger and more educated, reported higher household income, and used computers more frequently to manage their farms (table 2). On average, precision soil sampling adopters had about one year more formal education than nonadopters, and were (on average) about three years younger than producers who had not adopted the technology. Approximately 67% of the producers

Table 2. Comparison of Characteristics Between Adopters and Nonadopters of Precision Soil Sampling

	Mean		
Variable [a]	Adopter (n = 335)	Nonadopter (n = 492)	t-Test [b]
LIVEST	0.27	0.27	0.01
PROFIT	0.66	0.46	5.81**†
ACRES	1,020.00	650.00	4.97**†
OCROPS	0.26	0.22	2.28**†
LANDTEN	31.88	30.60	0.58
YVAR	545.61	506.73	2.16**†
AGE	47.87	50.59	−3.46**†
EDUC	14.73	13.99	4.80**
COM	0.67	0.51	5.12**
INCOME	0.38	0.30	2.41**†
EXTEN	0.59	0.54	1.52†
YRSADOPT	10.19	0.00	16.97**†
VRPKL	0.40	0.07	11.35**†

Note: Double asterisks (**) denote statistical significance at the 5% level.
[a] Variables are defined in table 1.
[b] † denotes t-test calculated assuming unequal variance.

who adopted soil sampling technology used computers as a farm management decision aid compared to nonadopters (51%). Adopters were more sanguine about the future profitability of precision agriculture (66%) than producers who had not adopted the technology (46%). Adopters also, on average, farmed more cotton acres (1,020 acres) compared to nonadopters (650 acres), which is consistent with the notion of scale economies, and the ability to spread the cost of soil sampling over more acres.

The difference in the percentage of total cropped acres devoted to cotton between adopters (26%) and nonadopters (22%) was significant at the 5% level (table 2). Therefore, on average, cotton producers adopting soil sampling devoted a smaller percentage of the total crop acres to cotton production (74%) than nonadopters (78%), suggesting that information obtained from soil sampling was likely used in tandem with production of other crops. Likewise, producers who adopted soil sampling were more likely to apply phosphorous (P), potassium (K), or lime using variable-rate technology (40%) as opposed to cotton producers who had not adopted the technology (7%). Producers who adopted precision soil sampling also reported greater yield variability compared to their counterparts, suggesting that adopters may use soil sampling as a tool to reduce the risks associated with yield variability. There were no differences between adopters and nonadopters of precision soil sampling with respect to livestock production, land ownership, or attitudes toward Extension services.

Univariate Comparison of Adopters with Abandoners

As observed from table 3, there were more similarities than differences between cotton producers who abandoned precision soil sampling and those who continued using the technology. Surprisingly, cotton producers who discontinued precision soil sampling

Table 3. Comparison of Characteristics of Producers Who Abandoned and Producers Who Continued the Use of Precision Soil Sampling

	Mean		
Variable [a]	Abandon (n = 56)	Continue (n = 279)	t-Test [b]
LIVEST	0.30	0.27	0.53
PROFIT	0.79	0.64	2.37**†
ACRES	1,394.00	943.00	1.64†
OCROPS	0.31	0.25	1.72†
LANDTEN	33.19	31.61	0.33
YVAR	548.66	545.00	0.09
AGE	48.32	47.78	0.38†
EDUC	14.39	14.80	−1.93†
COM	0.75	0.67	1.18†
INCOME	0.52	0.35	2.30**
EXTEN	0.88	0.86	0.22
YRSADOPT	3.70	11.70	−7.48**†
VRPKL	0.39	0.40	−0.17

Note: Double asterisks (**) denote statistical significance at the 5% level.
[a] Variables are defined in table 1.
[b] † denotes t-test calculated assuming unequal variance.

expressed that they were optimistic about the profitability of precision agriculture in the future. About 80% of the producers who discontinued precision soil sampling were optimistic about the future of precision agriculture. This question focused on precision agriculture in general and not specifically precision soil sampling. Respondents optimistic about the future of precision agriculture could be satisfied with other precision technologies they use, may know others who have profited from adoption of precision agriculture packages, or have confidence in research and development of precision agriculture systems. It is worth noting that variable-rate P, K, or lime application, yield variability, and computer use—all factors related to other precision agriculture devices—were not different between users and abandoners. Among producers who abandoned precision soil sampling (52%), the sum of farm and off-farm income was (on average) more than $150,000 per year, compared to producers who continued to use the technology (35%). As expected, the longer cotton producers used precision soil sampling, the more likely they were to continue using the technology. On average, producers who reported continued use of precision soil sampling had used the technology for about 12 years (compared to 3.7 years of use before abandonment). Operator age, sentiments about Extension services, land tenure, cotton acres operated, crop diversity, and livestock production were not found to be different between adopters and abandoners at the 5% level.

Model Estimation and Specification

The joint null hypotheses $A = B = 0$ for all coefficients were rejected at the 5% level (table 4). The correlation between the adoption and abandonment decisions was strong and significant ($\rho = 0.997$, Wald statistic = 21, df = 1). Khanna (2001) investigated the sequential adoption of site-specific management tools and also identified strong sample

Table 4. Bivariate Probit Sample Selection Model Estimation of Adoption and Abandonment of Precision Soil Sampling (standard errors in parentheses)

	Dependent Variable[a]			
	ADOPT (n = 827)		*ABANDON* (n = 335)	
Independent Variable[b]	Coefficient	Marginal Effect[c]	Coefficient	Marginal Effect[c]
Constant	–1.968** (0.764)		–4.822** (1.802)	
LIVEST	0.076 (0.106)	0.030 (0.041)	0.121 (0.181)	0.028 (0.059)
PROFIT	0.321** (0.101)	0.123** (0.038)	0.454** (0.181)	0.095* (0.053)
ACRES	0.216** (0.059)	0.083** (0.023)	0.232** (0.059)	0.041** (0.020)
OCROPS	0.281* (0.167)	0.108* (0.064)	0.667** (0.251)	0.173** (0.080)
LANDTEN	0.002 (0.002)	0.001 (0.001)	0.002 (0.002)	0.000 (0.001)
YVAR	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
AGE	0.019 (0.029)	0.007 (0.011)	0.128* (0.069)	0.039* (0.022)
QUADAGE	–0.0003 (0.000)	–0.0001 (0.000)	–0.001* (0.001)	–0.0004* (0.000)
EDUC	0.058** (0.023)	0.022** (0.008)	–0.006 (0.035)	–0.012 (0.011)
COM	0.181* (0.101)	0.069* (0.039)	0.279 (0.171)	0.061 (0.051)
INCOME	0.158 (0.097)	0.061 (0.038)	0.268* (0.154)	0.065 (0.051)
EXTEN	–0.027 (0.095)	–0.010 (0.037)	–0.010 (0.165)	0.001 (0.052)
YRSADOPT			–0.062** (0.018)	–0.021** (0.007)
VRPKL			–0.317** (0.152)	–0.091** (0.042)
ERS1	0.330 (0.248)	0.130 (0.099)	0.352 (0.297)	0.069 (0.105)
ERS5	0.303 (0.201)	0.120 (0.080)	–0.847* (0.444)	–0.167* (0.038)
ERS7	–0.013 (0.236)	–0.005 (0.091)	0.053 (0.347)	0.021 (0.113)
ERS9	0.132 (0.106)	0.051 (0.041)	–0.197 (0.186)	–0.082 (0.054)
ρ		0.997**		
Log Likelihood				–630
Wald Statistic[d] (H_0: $\boldsymbol{\beta} = 0$)				73.07
Wald Statistic[e] (H_0: $\rho = 0$)		20.86		

Notes: Single and double asterisks (*, **) denote statistical significance at the 10% and 5% levels, respectively.
[a] *ADOPT* = 1 if the farmer adopted precision soil sampling, 0 otherwise; *ABANDON* = 1 if the farmer discontinued using precision soil sampling, 0 otherwise.
[b] Independent variables are defined in table 1.
[c] Marginal effects for continuous variables are calculated as the change in the probability of adoption or abandonment for a unit change in the explanatory variable holding all other variables constant. The marginal effects of discrete (0, 1) variables are estimated as the change in probability of adoption/abandonment following a change in the dummy variable from 0 to 1. Marginal effects for abandonment are conditional on the decision to adopt.
[d] df = 18, critical value = 52 at 5% significance level.
[e] df = 1, critical value = 3.84 at 5% significance level.

selection bias. The high correlation between the selection and outcome equations is not surprising because producers who abandoned soil sampling must have adopted it at some point. In many empirical situations, the selection and outcome equations may be highly collinear when many of the same variables appear in both equations. As a result, the correlation between the disturbance terms of the equations is typically strong. Consequently, the signs, magnitude, and significance of regressors shared between the equations may in fact be an artifact arising from the highly nonlinear objective function rather than attributes of the sample.

Puhani (2000) and Nawata (1993) studied the collinear effects arising from FIML estimation of the Heckman probit selection model. Both found that when the correlation between the outcome and selection equations was strong, the effects typically expected from collinearity (sign switching, changes in coefficient magnitude, and inflated standard errors) were more likely. As a sensitivity analysis, the adoption and abandonment equations were estimated as separate probit regressions (table 5). The results of the selection model estimated with FIML appear to be robust with respect to collinearity between the adoption and abandonment sequences. The signs, magnitudes, and significance of the marginal effects estimated using FIML and the separate probit regressions were also similar, and conclusions drawn from both models are similar.

The null hypotheses of the exogeneity test could not be rejected in the *ADOPT* (Wald statistic = 6.50, df = 5, $P = 0.26$) or the *ABANDON* equations (Wald statistic = 8.22, df = 7, $P = 0.31$). Therefore, insufficient evidence exists to reject the null hypothesis that cotton acres, crop diversity, yield variability, computer use, and income were exogenous in the adoption equation; and that cotton acres, crop diversity, yield variability, computer use, income, variable-rate P, K, or lime, or the number of years soil sampling had been used were exogenous.

With the exception of *AGE* and *QUADAGE*, variance inflation factors were less than 2 for all variables in the *ABANDON* equation. The collinearity between *AGE* and *QUADAGE* was expected given the construction of these variables. Nonetheless, the high variance inflation factors of these variables suggest that failure to reject the null hypothesis that *AGE* and *QUADAGE* had no relationship with the decision variables should be interpreted carefully. A sensitivity check omitting the quadratic age term in the model is reported below.

Precision Soil Sampling Adoption

Cotton acreage (*ACRES*), perceptions about the future profitability of precision agriculture (*PROFIT*), the number of years of education (*EDUC*), and the use of a computer in farm management (*COM*) were positively correlated with the adoption of precision soil sampling, holding other factors constant (table 4). The percentage of total acres used to produce crops other than cotton (*OCROPS*) was positively related with the adoption of precision soil sampling, suggesting some knowledge spillover advantage from using the technology on multiple crops. Enterprise diversification (*LIVEST*), land tenure (*LANDTEN*), yield variability (*YVAR*), farmer age (*AGE*), farmer age squared (*QUADAGE*), pre-tax household income (*INCOME*), and perceptions about the usefulness of Extension (*EXTEN*) were not related with the decision to adopt precision soil sampling. The probability of adoption in other ERS farm resource regions was not significantly different from adoption in the Southern Seaboard region.

Table 5. Single Equation Probit Regressions of Adoption and Abandonment of Precision Soil Sampling (standard errors in parentheses)

	Dependent Variable [a]			
	ADOPT (*n* = 827)		*ABANDON* (*n* = 335)	
Independent Variable [b]	Probit Coefficient	Marginal Effect [c]	Probit Coefficient	Marginal Effect [c]
Constant	–1.932** (0.754)		–4.258** (1.893)	
LIVEST	0.073 (0.106)	0.028 (0.041)	0.118 (0.222)	0.020 (0.040)
PROFIT	0.321** (0.100)	0.123** (0.038)	0.378 (0.234)	0.058* (0.033)
ACRES	0.213** (0.061)	0.082** (0.023)	0.200** (0.078)	0.032** (0.013)
OCROPS	0.303* (0.171)	0.117* (0.066)	0.650* (0.376)	0.108* (0.063)
LANDTEN	0.002 (0.002)	0.001 (0.001)	0.000 (0.003)	0.000 (0.001)
YVAR	0.000 (0.000)	0.000 (0.001)	0.000 (0.000)	0.000 (0.001)
AGE	0.017 (0.029)	0.007 (0.011)	0.169** (0.076)	0.026** (0.012)
QUADAGE	0.000 (0.000)	0.000 (0.000)	–0.002** (0.001)	–0.000** (0.000)
EDUC	0.057** (0.023)	0.022** (0.009)	–0.030 (0.048)	–0.008 (0.008)
COM	0.183* (0.102)	0.070* (0.039)	0.247 (0.226)	0.038 (0.033)
INCOME	0.153 (0.098)	0.059 (0.038)	0.260 (0.197)	0.045 (0.035)
EXTEN	–0.028 (0.096)	–0.011 (0.037)	0.002 (0.198)	0.000 (0.033)
YRSADOPT			–0.073** (0.016)	–0.012** (0.002)
VRPKL			–0.409* (0.203)	–0.064** (0.032)
ERS1	0.291 (0.251)	0.115 (0.100)	0.305 (0.406)	0.060 (0.094)
ERS5	0.303 (0.215)	0.120 (0.086)	–1.136** (0.598)	–0.095** (0.024)
ERS7	–0.033 (0.231)	–0.126 (0.088)	0.197 (0.460)	0.037 (0.096)
ERS9	0.135 (0.106)	0.052 (0.041)	–0.353 (0.232)	–0.056 (0.035)
Log Likelihood	–513		–118	
Correctly predicted	539 (65%)		285 (85%)	
Wald Statistic [d] (H_0: $\boldsymbol{\beta} = 0$)	22.362** (13 df)		27.587** (17 df)	

Notes: Single and double asterisks (*, **) denote statistical significance at the 10% and 5% levels, respectively.

[a] *ADOPT* = 1 if the farmer adopted precision soil sampling, 0 otherwise; *ABANDON* = 1 if the farmer discontinued using precision soil sampling, 0 otherwise.

[b] Independent variables are defined in table 1.

[c] Marginal effects for continuous variables are calculated as the change in the probability of adoption or abandonment for a unit change in the explanatory variable holding all other variables constant. The marginal effects of discrete (0, 1) variables are estimated as the change in probability of adoption/abandonment following a change in the dummy variable from 0 to 1. Marginal effects for abandonment are conditional on the decision to adopt.

These results suggest that farmers who had more years of formal education, farmed more cotton acres, used computers in farm management, were optimistic about the future of precision agriculture, and allocated relatively more acres to crops other than cotton were more likely to adopt precision soil sampling for cotton production. These findings are consistent with the existing body of literature on adoption of various precision agriculture technologies in general (e.g., Khanna, 2001; Daberkow and McBride, 2003; Roberts et al., 2004). Surprisingly, though, age does not appear to be associated with the adoption decision. We surmised this might be due to collinearity between *AGE* and its square. As a sensitivity check, *AGE* was significant after eliminating the quadratic term. This check had no effect on the other coefficients with respect to direction and significance.

Precision Soil Sampling Abandonment

Cotton acres (*ACRES*), the percentage of acres devoted to other crops (*OCROPS*), farmer age (*AGE*), farmer age squared (*QUADAGE*), number of years precision soil sampling had been used (*YRSADOPT*), and variable-rate application of P, K, or lime (*VRPKL*) were all found to have a statistically significant correlation with abandoning precision soil sampling, holding all else constant (table 4). The signs of these variables were consistent with a priori expectations, with the exception of cotton acres (*ACRES*). Cotton acreage (*ACRES*) was positively associated with the probability of abandoning soil sampling. An alternative explanation concerning this variable is that larger cotton operations may have received increased managerial attention compared to smaller operations, and therefore the profitability of an investment in precision agriculture may be subject to a higher level of scrutiny. Conversely, larger operations may not have managerial time required to conduct (or perceive any value in) precision soil sampling. Higher levels of scrutiny may increase the likelihood of abandonment at even smaller margins below profit.

Variables not correlated with discontinuance of precision soil sampling (table 4) were enterprise diversification (*LIVEST*), land tenure (*LANDTEN*), yield variability (*YVAR*), number of years of formal education (*EDUC*), and perceptions about the usefulness of Extension (*EXTEN*). The probability of abandoning soil sampling was significantly lower in the Eastern Uplands region (*ERS5*) than in the Southern Seaboard region. The adoption rate for soil sampling by farmers in other ERS farm resource regions was not significantly different than in the Southern Seaboard region.

The finding that acres allocated to cotton production (*ACRES*) was positively correlated with discontinuance of precision soil sampling is consistent with results reported by Foltz and Chang (2002) and Barham et al. (2004). These studies found that adopters and abandoners share many of the same characteristics. The univariate comparisons of adopters and abandoners in our investigation show that producers discontinuing soil sampling planted more acres to cotton than producers who continued using the technology. Those who adopted precision soil sampling planted an average of 1,020 acres of cotton, while those who abandoned precision soil sampling planted an average of 1,394 acres. This lends some support to the alternative hypothesis stated earlier that larger acres receive increased managerial attention, and therefore the performance of a technology is subject to a higher level of scrutiny. An increased level of attention paid to the performance of precision soil sampling could foster abandonment decisions when even moderately poor performance is observed.

The positive coefficient associated with non-cotton acreage as a percentage of total cropped acres is consistent with the previous hypothesis for this variable. As the percentage of total area devoted to cotton increased, the likelihood of abandoning soil sampling decreased. This finding suggests that crop enterprise diversification increases the probability of abandoning precision soil sampling. It is possible that while some farmers may use crop diversification as a risk-managing strategy, others may use information from soil sampling, and allied site-specific technologies, to manage risk.

Age was positively related with soil sampling discontinuance, which is consistent with hypotheses concerning the effects of shortened planning horizons of decision making. The square of age was negatively associated with discontinuance, suggesting that with experience comes understanding of how to successfully apply information from soil testing. The most likely age when operators abandoned precision soil sampling was 49. Younger, less experienced farmers appear more likely to abandon soil sampling, perhaps out of frustration. But with age comes experience, and the likelihood of abandoning soil sampling decreases. Beyond 49 years, the effect of experience decreases and the role of a shortened planning horizon takes effect, increasing the likelihood of abandonment.

The negative coefficients associated with the number of years adopted and the use of variable-rate application of inputs are consistent with the hypotheses stated earlier. Continuing the use of precision soil sampling in subsequent years after adoption demonstrates that the perceived benefits were greater than associated costs. Using data obtained from an information-gathering technology, such as precision soil sampling, for variable-rate application of inputs also suggests that the value obtained from adoption is greater than the associated costs.

Summary and Conclusion

Cotton farmer decisions regarding the adoption and abandonment of precision soil sampling were analyzed as a function of farm and farmer characteristics. The results from a sequential adoption-abandonment model suggest that younger farmers, those with larger cotton acreages who had positive perceptions about the future profitability of precision agriculture, or those who used a computer in farm management were more likely to adopt precision soil sampling. Results indicate that farmers who allocated more acres to the production of crops other than cotton were more likely to adopt precision soil sampling for cotton production. Thus, farmers may have transferred technology familiarity and use from other crops to cotton. Of those who adopted, younger farmers in the Eastern Uplands region, those who used precision soil sampling technology a greater number of years, or those who utilized variable-rate application of inputs were less likely to abandon. Results also revealed that adopters with larger cotton acreages were more likely to abandon precision soil sampling, suggesting that farmers operating larger acreages of cotton applied greater scrutiny to management practices, or that individuals with larger operations have less time to manage detailed soil sample information. In addition, producers may not perceive any value in precise measurement of soil characteristics in a field sampled over several seasons since this information is generally applicable for several years.

The marketing efforts of agribusiness firms could benefit from tailoring efforts toward younger farmers or farms with larger cotton acreages as they attempt to promote precision soil sampling services. An important conclusion drawn from this research is that agribusiness firms wanting to maintain the use of precision soil sampling technology by producers could benefit from promoting other technologies and practices that make use of the site-specific data gathered from soil sampling. Extension personnel could create educational programs, emphasizing the application of precision soil sampling data in cotton production. Expanding adoption/abandonment analyses could also be important for developing an understanding of the use and discontinuance of other precision farming methods, including aerial imagery and other remote-sensing technologies, controlled drainage systems, and yield monitoring. Similar patterns of adoption and abandonment may imply that producers perceive the benefits of precision agriculture technologies to be initially high, but after repeated use over time, these technologies become routine, with less immediate value attributed to them.

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