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Factors Influencing Farmer Adoption of Portable Computers for Site-Specific Management: A Case Study for Cotton Production

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

Personal digital assistants (PDA) and handheld global positioning systems (GPS) have become increasingly important in cotton production but little is known about their use. This research analyzed the adoption of PDA/handheld GPS devices in cotton production. A younger farmer who used a computer in farm management and had a positive perception of Extension had a greater likelihood of adopting the devices. In addition, farmers who used complementary remote sensing, plant mapping, and grid soil sampling information were more likely to use PDA/handheld GPS devices. Finally, the COTMAN in-field decision support program from Extension also positively impacted adoption.

Key Words: decision support, information technology, precision farming technology, variable rate technology

JEL Classifications: D21, Q12, Q16

Advances in information technologies used in precision agriculture have increased the degree to which spatial variation in cropland and crop performance can be measured (Roberts et al., 2004). Technologies specific to agriculture used to measure spatial variability include grid or management zone soil sampling and yield monitors. In addition to the information technologies that have been developed to collect precision farming data, a number of more broad-based information technologies are playing an increasingly important role in precision farming. For example, remotely sensed satellite and aerial imagery have been adopted for many agricultural management decisions (Griffin et al., 2004; Larson et al., 2008). Other information technologies with many potential applications in

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Jonathan C. Walton is extension area specialist, James A. Larson is associate professor, Dayton M. Lambert is assistant professor, and Roland K. Roberts and Burton C. English are professors at the University of Tennessee, Knoxville, TN. Sherry L. Larkin is associate professor at the University of Florida, Gainesville, FL. Michele C. Marra is professor at North Carolina State University, Raleigh, NC. Steven W. Martin is associate professor and extension economist at Mississippi State University, Stoneville, MS. Kenneth W. Paxton is professor at Louisiana State University, Baton Rouge, LA. Jeanne M. Reeves is director of Agricultural Research at Cotton Incorporated, Cary, NC.

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farm management and precision farming are personal digital assistants (PDA) and other handheld computers with global positioning systems (GPS). This research focuses on the factors influencing the adoption of PDA/handheld GPS devices in precision cotton production.

At a basic level, cell phones are one type of PDA/handheld GPS device that have been widely adopted by farmers to maintain contact with spouses, employees, input suppliers, commodity buyers, and others involved in farming operations (Vellidis et al., 2007). Other PDA/handheld GPS devices with additional software applications and computing capacity have been used for field boundary mapping; yield monitoring; sharing data across precision farming technologies; managing remotely sensed images, yield maps, and soil maps; collecting additional field information to enhance existing soil and yield data; identifying problem areas in fields; feeding input prescription maps into controllers on variable rate technology (VRT) applicators; and recording inputs as applied using VRT for identity preservation and environmental compliance (Darr et al., 2003; Fischer, 2007; Flores, 2003; Muzzi, 2004; Robinson, 2006; Stombaug, Koostra, and Shearer, 2003; Sudbrink Jr. et al., 2003; Wang, Zhang, and Wang, 2006). PDA/handheld GPS devices also have potential applications in precision livestock management including pasture forage measurement and sampling, determining the location of water and salt in pastures, setting up pasture paddocks for management intensive grazing, and monitoring animal location and status (Butler et al., 2006; Griffin, Evans, and Oswald, 2003; Yule, Lawrence, and Murray, 2005).

With regard to in-field data collection, decision support software programs for cotton such as COTMAN (Computerized Cotton Management System) and CottonLOGIC have been integrated with PDA/handheld GPS devices to facilitate infield collection of characteristics of the growing crop (Bange et al., 2004; Cochran et al., 1998; Hearn and Bange, 2002). Producers and crop consultants have used PDA/handheld GPS devices with in-field software programs to verify the accuracy of spatially referenced field data (i.e., ground truth) and to facilitate guided scouting to address problematic areas of a cotton field (Robinson, 2006). Guided scouting using remotely sensed maps loaded into a PDA/handheld GPS device has been used to increase the efficiency and success of applications of fertilizers, pesticides, plant growth regulators, and harvest aids in cotton production (Robinson, 2006).

Researchers also have examined the possibility of using wireless local area networks and PDA/handheld GPS devices to manage equipment, downloading maps for guided scouting, and sharing data among applications (Flores, 2003; McKinion et al., 2003, McKinion et al., 2004a; McKinion et al., 2004b; Vivoni and Camilli, 2003). Limits on existing communication infrastructure in some rural areas make the transmission of some types of time sensitive data inefficient if not impossible. McKinion et al. (2003, 2004a, 2004b) looked at the transmission of multispectral images that can be used to determine VRT application of inputs in cotton production. After transmission through the wireless local area network, images were carried to the field using PDA/handheld GPS devices for the purpose of ground truthing. Thus, PDA/handheld GPS devices have a great deal of potential for farm management and agricultural production decision making. Notwithstanding the potential time and cost savings from these technologies, site-specific management of farm fields is more management intensive compared with traditional whole-field management because of the additional time and skills required for such activities as data collection, verification, interpretation, analysis, and implementation.

To further understand the roles of PDA/handheld GPS devices in precision agriculture, it is useful to examine the role of computers in farm management. The development of affordable, efficient computer technology has facilitated the storage, processing, and interpretation of large amounts of information. Extensive research has investigated the farm and farmer characteristics associated with the adoption of computers in agriculture (e.g., Amponsah, 1995; Batte, Jones, and Schnitkey, 1990; Putler and Zilberman, 1988; Smith et al., 2004). These studies found that computer adoption in agriculture was influenced by characteristics such as farm size, farmer education, and farmer age.

Putler and Zilberman (1988) found that computer use for business transactions and accounting purposes was much higher than for use in decisions directly tied to production. However, since the completion of their study, the development of portable computing devices that can be used in precision agriculture warrants further examination into the use of computer technology as an in-field decision-aid for production. Thus, the objective of this research was to identify the farm and farmer characteristics that affect the adoption of PDA/handheld GPS devices for variable rate technology decision making in cotton production. An understanding of these factors has implications for agribusiness firms engaged in the development and promotion of precision agricultural technologies as well as for Extension personnel developing educational curricula and support programs for farmers engaged in or considering precision agriculture.

Data

The data for this study were 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 comprehensive survey instrument queried producers about the extent to which precision agricultural technologies were used on their farms as well as information about the general structure and characteristics of their farming operations. Farmers also answered questions regarding the costs and profitability of precision agriculture, as well as their perceptions of precision agriculture. Producers reported the total number of years they had used a PDA/handheld GPS device to make variable-rate management decisions. This information was used to measure the level of PDA/handheld GPS adoption and to examine the production decisions made with a PDA/handheld GPS device.

The sample frame of 12,243 potential cotton producers in the 11 states was provided by the Cotton Board in Memphis, Tennessee (Skorupa, 2004). The mailing list included producers who were required by law to report cotton sold to the Cotton Board between August 1, 2003 and July 31, 2004. Sellers who were not producers of cotton such as brokers and gins were eliminated from the list by the Cotton Board. Using mail survey procedures described by Dillman (1999), the questionnaire, a postage-paid return envelope, and a cover letter explaining the purpose of the survey were sent via first class mail on January 28, 2005. A post card reminding farmers to complete the questionnaire was sent on February 4, 2005. A follow-up reminder to farmers who did not respond to the first mailing was sent on February 23, 2005. The mailing included a cover letter reiterating the importance of the survey, another copy of the questionnaire, and another postage-paid return envelope. No further mailings were made and no follow-up was made with the nonrespondents because of budget limitations. Of 12,243 surveys mailed, 200 were returned either undeliverable or by farmers indicating they no longer produced cotton. Of the remaining 12,043 cotton farmers, 1,216 responded to the questionnaire giving a response rate of 10%. There were 765 observations available for analysis of PDA/handheld GPS device adoption after eliminating observations with missing data. The comprehensive questionnaire was long and complex, which may have been a factor in the low response rate. Farmer interest in precision agriculture may have diminished because of low prices at the time of the survey and also may have negatively influenced the response rate (Anderson, 2004).

The sample of 765 observations was compared with the 2002 Census of Agriculture to evaluate how well the respondents represented the population of cotton farmers in the 11 surveyed states (U.S. Department of Agriculture, National Agricultural Statistics Service, 2004). Cotton farms from the Census were defined using the North American Industrial Classification System (cotton code 111920) and may be representative of larger commercial cotton operations. The average age of 49 years for farmers in the sample was less than the average age of 52 years for the Census (Table 1). In addition, the average size of the cotton enterprise was larger in the sample than in the Census—818 acres compared with 635 acres (Table 1). The percentage of owned land to total land farmed was

Table 1. Variable Definitions, Hypothesized Signs, Means, and Standard Deviations in the PDA and Handheld GPS Adoption Equation

Variable	Definition	Hypothesized Sign	Mean	SD
Farmer Characteristics				
LOGAGE	Natural log of age in years of the primary decision maker	−	3.86 (49 years)	0.24
EDUC	Number of years of formal education	+	14.35	2.21
COM	Equals one if the farmer used a computer for farm management and zero otherwise	+	0.59	0.49
EXTEN	Equals one if the farmer felt that Extension was useful in making precision farming decisions and zero otherwise	+	0.57	0.50
Farm Characteristics				
ACRES	Average of cotton acreage grown in 2003 and 2004 (1,000s acres)	+	0.818	0.967
OCROPS	Percentage of noncotton acreage to total cropped acreage	+	23.73	27.12
LIVEST	Equals one if the farming operation includes livestock and zero otherwise	−	0.28	0.45
LANDTEN	Percentage of owned land to total land farmed	+	30.86	31.25
YVAR	Difference between the farmer's estimates of average yields for the most productive 1/3 of and the least productive 1/3 of a typical field	+	530.34	249.41
INCOME	Equals one if pretax household income was greater than $150,000	+	0.33	0.47
Information Technologies				
RS	Equals one if remote sensing was used to gather crop data	+	0.12	0.32
COTMAN	Equals one if COTMAN plant mapping software was used and zero otherwise.	+	0.05	0.22
YM	Equals one if the farmer used a yield monitor and zero otherwise	+	0.10	0.31
SSM	Equals one if the farmer used soil survey maps and zero otherwise	+	0.21	0.41
ZSS	Equals one if the farmer used management zone soil sampling and zero otherwise	+	0.11	0.32
GSS	Equals one if the farmer used grid soil sampling and zero otherwise	+	0.22	0.41
Variable-Rate Application Decisions				
SELF	Equals one if the farmer generated maps to apply inputs and zero otherwise	+	0.03	0.17
CONSULT	Equals one if a consultant generated maps to apply inputs and zero otherwise	+	0.06	0.23

Table 1. Continued

Variable	Definition	Hypothesized Sign	Mean	SD
DEALER	Equals one if a fertilizer or chemical dealer generated maps to apply inputs and zero otherwise	+	0.09	0.29
VRINSGR	Equals one if variable-rate application of growth regulator and/or insecticide were used and zero otherwise	+	0.05	0.21
VRHA	Equals one if variable-rate application of harvest aids was used and zero otherwise	+	0.05	0.21
VRPKL	Equals one if variable-rate application of P, K, and/or L were used and zero otherwise	+	0.21	0.41

31% in the sample compared with 35% in the Census (Table 1). Producers who reported using computers in farm management averaged 59% in the sample and 52% in the Census (Table 1). These comparisons suggest that the farms in the sample may be larger on average than the cotton farms in the Census. Larger farms have higher adoption rates for precision agriculture technology (Daberkow and McBride, 1998). Thus, the data used in this study are useful because these farmers are more likely to be users of site-specific technologies such as PDA/handheld devises. Notwithstanding the numerical differences between the sample and the Census, the means of the four characteristics used from the Census fell within the 95% confidence intervals of the sample means (Table 1). Thus, the comparison with the 2002 Census of Agriculture does not suggest an important response bias even though the response rate was not large. Still the reader is urged to use caution drawing inferences to the population of all cotton producers in the 11 states.

Methods and Procedures

Analytical Framework

Farmers are assumed to maximize expected utility over a planning horizon. Due to the unobservable nature of utility, a random utility model is used to analyze the farmer's decision to adopt a PDA/handheld GPS device (Kennedy, 1992). Let U_i^A represent the expected utility from adopting a PDA/handheld GPS device and U_i^{NA} represent the expected utility from not adopting a PDA/handheld GPS device. Thus, the difference in an individual farmer's utility for the two choices is $U_i = U_i^A - U_i^{NA}$. The farmer is expected to adopt a PDA/handheld GPS device when $U_i > 0$, and not adopt the device when $U_i < 0$.

Utility for farmer *i* is stochastic, represented as:

$$(1)\qquad U_{\mathrm{i}} = \beta' x_{\mathrm{i}} + \varepsilon_{\mathrm{i}}.$$

The deterministic component of utility ($\beta' x_{\mathrm{i}}$) is hypothesized to be a function of exogenous variables (x_{i}) including personal attributes and farm characteristics, and the average effect of the exogenous variables across respondents on the adoption decision (β). Stochastic components affecting utility are represented by random disturbances (ε_{i}). While U_i is unobservable, the decisions to adopt (*A*) are observed as a binary variable (Khanna, 2001):

$$(2)\qquad A_i = 1(\text{if } U_i^A > U_i^{NA});\text{else } A_i = 0\,(\text{if } U_i^A < U_i^{NA}).$$

Multiplication of the unobserved variable U_i by any positive constant does not change the interpretation of A_i. Thus, it is common to assume that the variance of the error term is constant (Maddala, 1986). In this study, we use logistic regression to analyze adoption patterns, and therefore assume that $\mathrm{Var}(\varepsilon_i) = \pi^2/3$. Under this assumption, the relationships between Equations (1) and (2) yield:

$$P_i = \Pr(A_i = 1) = \Pr(U_i^A > 0) = \Pr[\varepsilon_i > -(\beta' x_i)] \\ = 1 - \Lambda[-(\beta' x_i)], \tag{3}$$

where P_i is the probability of adoption, $\Pr(A_i = 1)$ is the probability of positive response to the adoption question, and Λ is the logistic cumulative distribution function. From the symmetric qualities of the logistic distribution:

$$1 - \Lambda[-(\beta' x_i)] = \Lambda(\beta' x_i). \tag{4}$$

Relating Equation (3) to Equation (4), the probability of adoption is therefore:

$$P_i = \Lambda(\beta' x_i). \tag{5}$$

Given the probability stated in Equation (5), the sample likelihood function is:

$$L = \prod_{A_i=1} \Lambda(\beta' x_i) \prod_{A_i=0} \Lambda(-\beta' x_i). \tag{6}$$

Maximum likelihood is used to estimate Equation (6). In turn, estimates are used to predict the probability of adoption. Identification of characteristics influencing the adoption decision is determined by the sign and significance of the parameter estimates and the evaluation of probabilities (Kennedy, 1992).

Comparison of Sample Means

Comparisons of characteristics between the different sample subsets were made to provide further insight into the factors motivating PDA/handheld GPS devices adoption. Adopters were compared with those who did not adopt. An *F* test was used to determine if the variances of each subset were significantly different. The means for each of the observed farm and farmer characteristics were compared using an appropriate *t*-test, assuming equal or unequal variances, depending on the results of the *F* test. When the variances were unequal, the degrees of freedom for the *t*-tests were adjusted using Satterthwaite's correction (Lentner and Bishop, 1993).

Empirical Model

The empirical model for the adoption of PDA/handheld GPS devices was specified as follows:

$$\begin{aligned} PDA_i = {} & \beta_0 + \beta_1 LOGAGE_i + \beta_2 EDUC_i \\ & + \beta_3 COM_i + \beta_4 EXTEN_i + \beta_5 ACRES_i \\ & + \beta_6 OCROPS_i + \beta_7 LIVEST_i \\ & + \beta_8 LANDTEN_i + \beta_9 YVAR_i \\ & + \beta_{10} INCOME_i + \beta_{11} RS_i \\ & + \beta_{12} COTMAN_i + \beta_{13} YM_i + \beta_{14} SSM_i \\ & + \beta_{15} ZSS_i + \beta_{16} GSS_i + \beta_{17} SELF_i \\ & + \beta_{18} CONSULT_i + \beta_{19} DEALER_i \\ & + \beta_{20} VRINSGR_i + \beta_{21} VRHA_i \\ & + \beta_{22} VRPKL_i + \beta_{23} ERS1_i + \beta_{24} ERS5_i \\ & + \beta_{25} ERS7_i + \beta_{26} ERS9_i + e_i, \end{aligned} \tag{7}$$

where *PDA* equals one if farmer *i* adopted a PDA/handheld GPS device (zero otherwise), β_1 through β_{26} are parameters to be estimated using maximum likelihood, *e* is a random error term, with $E(e) = 0$ and $\mathrm{Var}(e) = \pi^2/3$. Definitions of the independent variables along with means and hypothesized signs are in Tables 1 and 2.

Factors Hypothesized to Influence Adoption of PDA/Handheld GPS Devices

Four farmer characteristics were hypothesized to influence the PDA/handheld device adoption decisions of cotton farmers (Table 1). The natural log of farmer age (*LOGAGE*) was expected to be negatively associated with adoption of a PDA/handheld GPS device (Batte, Jones, and Schnitkey, 1990; Roberts et al., 2004). The logarithmic transformation of age allows for risk aversion behavior as the producer becomes older. Thus, our hypothesis with the logarithmic transformation is that cotton producers at a younger age have a longer time horizon over which they can make adjustments, offset the uncertain learning costs, and accumulate the uncertain benefits of the technology. But as a farmer matures, their planning horizon shortens, they will be more likely to have "fine-tuned" their managerial skills, less interested in changing their production plans, and less likely to adopt new technologies. The number of years of formal education (*EDUC*) was expected to positively influence adoption. Higher levels of formal education may increase the analytical ability of farm decision makers dealing with the volume and intricacy of data associated with precision agriculture (Batte,

Table 2. Regional Variables in PDA/Handheld GPS Adoption Equation

State/	Farm Resource Region[a]				
Variable	*ERS*1	*ERS*5	*ERS*6[b]	*ERS*7	*ERS*9
State			Percentage of Total Observations		
TN		0.20			9.00
VA			2.88		
GA			17.15	1.31	
NC			17.41		
SC			4.45	1.31	
AL		4.71			
MS			0.20		12.70
LA			0.80		6.81
FL				1.83	
MO	3.66				
AR					8.25
Total	3.66	4.91	42.89	4.45	36.76
Variable					
Mean	0.035	0.052	0.503	0.045	0.365
Hypothesized Sign	+/−	+/−	+/−	+/−	+/−

[a] *ERS*1 is Heartland, *ERS*5 is Eastern Uplands, *ERS*6 is Southern Seaboard, *ERS*7 is Fruitful Rim, and *ERS*9 is Mississippi Portal.
[b] Reference region.

Jones, and Schnitkey, 1990). In much the same way, the use of a computer in farm management (*COM*) is expected to positively influence the adoption decision. Because computer technology is either integrated into precision agricultural technology or it is necessary to convey and manipulate precision farming data, computer use for farm management is likely tied to PDA/handheld GPS device adoption decisions through previous experience with computers (Daberkow and McBride, 1998). Farmers who felt that Extension was helpful in making precision farming decisions (*EXTEN*) were expected to be more likely to adopt a PDA/handheld GPS device. The availability of services such as Extension provides information to the farmer in investment decision making. Such services may reduce some of the perceived risk associated with adoption of new technologies (Roberts et al., 2004).

The following characteristics of the farm operation were hypothesized to influence adoption of PDA/handheld GPS devices (Table 1). The number of cotton acres planted (*ACRES*) represents a measure of enterprise size and is hypothesized to be positively related with adoption of these devices. When the fixed costs associated with computer technologies are spread over a larger crop area, barriers to adoption are less prohibitive (Fernandez-Cornejo, Beach, and Huang, 1994; Putler and Zilberman, 1988; Roberts et al., 2004). Similarly, learning costs associated with adoption may be spread over a larger number of acres thereby increasing the probability of adoption (Batte and Johnson, 1993). Farmers operating larger cotton acreages are also expected to have greater demand for technology to facilitate the handling of large amounts of spatially-referenced data associated with the crop area. The percentage of total cropped acres devoted to other crops (*OCROPS*) is expected to positively influence adoption. Farmers who place greater emphasis on crops such as grains and oilseeds are expected to transfer the use of precision agricultural technologies from those crops to cotton. An enterprise mix that includes cotton along with other crops which have higher precision agriculture adoption rates could influence the adoption of technologies in cotton production (Griffin et al., 2004). Enterprise diversification, represented by livestock ownership (*LIVEST*), is expected to negatively influence adoption of PDA/handheld GPS devices. Fernandez-Cornejo, Beach, and Huang

(1994) found that livestock production had a negative impact on the adoption of integrated pest management technologies. Management of an enterprise not directly related to crop agriculture could reduce the operator's ability to devote time to managing crops. The percentage of total acres owned (*LANDTEN*) is hypothesized to be positively related with adoption of PDA/handheld GPS devices. Farmers who control land through cash rental are not as likely to invest in precision farming applications for that land unless they have long term rental contracts. Some spatially referenced data may be useful over several growing seasons, and land ownership may ensure information obtained from such an investment is applicable for several years (Daberkow and McBride, 1998). Yield variability (*YVAR*) is hypothesized to be positively related with adoption of PDA/handheld GPS devices. The presence of greater yield variability increases the level of management intensity and the level of variability in required inputs. Technologies that increase management and input application efficiency may also increase profitability (Larson and Roberts, 2004). Higher income levels (*INCOME*) are expected to be positively related with adoption of these devices. Due to the substantial costs associated with some precision farming technologies, higher income could improve the farmer's ability to invest in more advanced electronic technologies (Rogers, 1983; Daberkow and McBride, 1998).

PDA/handheld GPS devices may complement other information technologies such as remote sensing, plant mapping, yield monitoring, and precision soil sampling (Barham et al., 2004). Consequently, the farmer's use of these and other information technologies were included in the model to explain adoption of PDA/handheld GPS devices. The use of remote sensing (*RS*), in-field decision support software (*COTMAN*), and yield monitor (*YM*) technologies to gather spatially oriented crop data are expected to positively influence the adoption of PDA/handheld GPS devices. Technologies used to generate field variability maps may require ground truthing using technologies such as PDA/handheld GPS devices to identify problems and generate spatially coordinated input prescriptions (Robinson, 2006). The use of soil survey maps (*SSM*) that could be digitized and loaded into a computer is expected to positively influence the adoption of PDA/handheld GPS devices. Knowledge of in-field soil type variability may be augmented by technologies that enable more intensive ground truthing. Precision soil sampling, whether by management zone (*ZSS*) or grid (*GSS*) soil sampling, is expected to increase the probability of PDA/handheld GPS device adoption. Technologies supported by site-specific data could benefit from the use of additional technologies that facilitate spatially referenced ground truthing.

Variable-rate application of these inputs requires geographically referenced ground truthing and geographically referenced control of the variable-rate application procedure. The source of the maps used to make variable-rate applications of inputs may also play a role in the adoption of a PDA/handheld GPS device. Farmers generating their own maps for variable-rate application (*SELF*) are hypothesized to adopt PDA/handheld devices more frequently (Larson et al., 2008). PDA/handheld GPS devices may also facilitate storage and transfer of spatially referenced field and crop data. In addition, farmers who obtain maps for variable-rate application from consultants (*CONSULT*) or fertilizer or chemical dealers (*DEALER*) are hypothesized to more likely adopt PDA/handheld GPS devices (Larson et al., 2008). Farmers may want to audit input application recommendations provided by outside sources. A PDA/handheld GPS device could facilitate this process. For the *SELF, CONSULT*, and *DEALER* explanatory variables, the reference category included farmers who did not use map-based VRT.

As indicated earlier, maps stored in PDA/handheld GPS devices are used to guide field scouting prior to variable-rate application of certain cotton inputs (Robinson, 2006). Thus, several variables indicating that adopters were using selected variable-rate input technologies were included in the logit model. The VRT decisions for fertilizer, insecticides, plant growth regulators, and harvest aids (boll openers, defoliants, and desiccants applied to facilitate harvest) are most likely to be associated with technology packages that include precision soil sampling, plant mapping and/or remote sensing, and a PDA/handheld GPS device (Robinson, 2006). Variable-rate applications of harvest aids (*VRHA*), insecticides, and plant growth regulators (*VRINSGR*) are expected to positively affect PDA/handheld GPS device adoption (Robinson, 2006). In addition, variable-rate application of phosphorus, potassium, and lime (*VRPKL*) is expected to positively influence the adoption (Robinson, 2006).

The U.S. Department of Agriculture, Economic Research Service farm resource regions (Table 2) were included in the logit model to test if cotton producers in the Heartland (*ERS*1), Eastern Uplands (*ERS*5), Fruitful Rim (*ERS*7), and Mississippi Portal (*ERS*9) regions had higher or lower probabilities of adopting PDA/handheld GPS devices than cotton producers in the Southern Seaboard (*ERS*6) region (U.S. Department of Agriculture, Economic Research Service). The Southern Seaboard region was the reference group because it produced the largest number of survey responses.

Logit Model Estimation, Evaluation, and Analysis

Equation (7) was estimated using logistic regression. White's (1980) heteroskedastic-robust standard errors were used to estimate the standard errors of the coefficients. Overall significance of the model was tested using a likelihood ratio test. The presence of collinear relationships among explanatory variables may influence the significance and inferential power of coefficients. Variance inflation factors were used to detect the presence of these collinear relationships. Variance inflation factors were calculated using the squared multiple correlation coefficient from the regression of each explanatory variable on all other explanatory variables. As the degree of variation in each individual explanatory variable explained by all other explanatory variables increases, the value of the variance inflation factor increases. Variance inflation factors greater than 10 are indicative of collinearity (Chatterjee and Price, 1991).

The potential exists for endogenous relationships among some farmer and farm characteristics and the decision to adopt a PDA/handheld GPS device. Complementary relationships among technologies can affect farmer perceptions of the expected value of a decision (Barham et al., 2004). Variables in Equation (7) that were hypothesized to be potentially endogenous include use of computers in farm management (*COM*), cotton acreage (*ACRES*), percentage of total cropped acreage devoted to other crops (*OCROPS*), yield variability (*YVAR*), household income (*INCOME*), use of remote sensing (*RS*), use of a yield monitor (*YM*), use of plant mapping (*COTMAN*), soil survey maps (*SSM*), soil sampling by management zone (*ZSS*), soil sampling by grid (*GSS*), variable-rate application of insecticides and plant growth regulators (*VRINSGR*), variable-rate application of harvest aids (*VRHA*), and variable-rate application of phosphorus, potassium, and lime (*VRPKL*). PDA/handheld GPS devices could facilitate the management of more crop acres and increase the efficiency of management decisions, which could lead to lower yield variability. Data handled in a PDA/handheld GPS device is often first manipulated and transferred through other types of computer technology. Endogeneity would be introduced if the computer-use decision facilitated the use of a PDA/handheld GPS device. The use of a PDA/handheld GPS device has the potential to increase management efficiency increasing profit and thus increasing income reported by the producer. Increases in the efficiency of data handling incurred through the adoption of a PDA/handheld GPS device may result in decisions to adopt variable-rate application of inputs or more intensive soil analysis methods.

Using a procedure outlined by Rivers and Vuong (1988), each potentially endogenous variable was regressed against all other exogenous variables, and a vector of instrumental variables.[1] The residuals from these equations

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[1] The instruments used along with the original explanatory variables in the logit model were annual precipitation, July humidity, and January sunshine from the Area Resource File (www.arfsys.com); a population interaction index (www.ers.usda.gov/Data/PopulationInteractionZones); and variables indicating whether the county was classified as a manufacturing dependent county, low employment county, or low education county (www.ers.usda.gov/Data/TypologyCodes).

were then included as additional explanatory variables in a separate estimation of the adoption equation. Generalized residuals were calculated for potentially endogenous binary variables (Vella, 1992). The residuals were tested for joint significance using a Wald test (Wooldridge, 2002). Failure to reject the null hypothesis of joint significance provides evidence that the variables are statistically exogenous.

To facilitate the interpretation of the logit model, log odds (*ODDS*) ratios for individual coefficients (Cody and Smith, 2005) were estimated as:

$$(8) \qquad ODDS_k = \frac{P(A=1)}{1-P(A=1)} = \exp(\beta_k)^{c-d},$$

where $P(A = 1)$ is the probability of adopting a PDA/handheld GPS device, β is the estimated parameter on explanatory variable k, and c and d are constants. Equation (8) is the change in the odds of being in the adopter group relative to the nonadopter group for any change in the corresponding explanatory variable, $c–d$. The log odds for each estimated coefficient was used to evaluate how the odds of being an adopter of a PDA/handheld GPS device vary as the significant explanatory variable of interest changes by a specified interval, holding all other variables constant. In a sensitivity analysis, the probabilities of a farmer using a PDA/handheld GPS device as influenced by selected combinations of statistically significant complementary information technology and VRT decision variables were evaluated using Equation (5) and the coefficients estimated in Equation (7).

Results

Comparison of Sample Means

Means of the observed farm-operation and farmer-characteristic variables for the sample subsets of adopters and nonadopters were significantly different for all variables except livestock ownership (*LIVEST*), percentage of total crops acres devoted to crops other than cotton (*OCROPS*), land tenure (*LANDTEN*), and management zone soil sampling (*ZSS*) (Table 3). On average, PDA/handheld GPS device users in the sample were younger, farmed more cotton acres, reported higher spatial yield variability, utilized computers more in farm management, and reported higher levels of income. In addition, nonadopters felt more strongly than adopters that Extension should provide greater precision farming outreach. The use of other precision farming technologies was also significantly higher among adopters of PDA/handheld GPS devices.

Table 3. Comparison of Characteristics between Adopters and Nonadopters of PDA/Handheld GPS Devices

Variable[a]	Adopter Mean	Nonadopter Mean	T-value[bc]
Farmer Characteristics			
AGE	44.59	49.57	−3.78**†
EDUC	14.84	14.28	2.21**
COM	0.84	0.56	6.38**†
EXTEN	0.70	0.55	2.70**
Farm Characteristics			
ACRES	1,447.74	736.75	3.59**†
OCROPS	0.27	0.23	1.70
LIVEST	0.26	0.28	−0.35
LANDTEN	30.36	30.93	−0.16
YVAR	627.55	517.85	3.90**
INCOME	0.44	0.32	2.26**
Information Technologies			
RS	0.31	0.09	4.28**†
COTMAN	0.18	0.04	3.50**†
YM	0.33	0.08	4.91**†
SSM	0.24	0.10	3.06**†
ZSS	0.29	0.21	1.66
GSS	0.55	0.16	7.02**†
Variable-Rate Application Decisions			
SELF	0.10	0.02	2.49**†
CONSULT	0.18	0.04	3.36**†
DEALER	0.20	0.08	2.70**†
VRINSGR	0.22	0.03	4.30**†
VRHA	0.20	0.03	3.83**†
VRPKL	0.59	0.17	7.65**†
N	87	678	

[a] Variables are defined in Tables 1 and 2.

[b] Significance at the 5% and 10% levels denoted by ** and * respectively.

[c] *t*-test assuming unequal variance denoted by †.

Model Evaluation

Variance inflation factors for all variables were less than three, suggesting multicollinearity was not a serious problem with respect to inference. The null hypothesis was that all regression coefficients were equal to zero at the 5% level (likelihood ratio test = 171, df = 26). The model correctly predicted 92% of the adopt-not adopt responses (Table 4). The Wald test failed to reject the joint (null) hypothesis that *COM*, *ACRES*, *OCROPS*, *YVAR*, *INCOME*, *RS*, *COTMAN, YM*, *SSM*, *ZSS*, *GSS*, *VRINSGR*, *VRHA*, and *VRPKL* were exogenous ($\chi^2 = 15.05$; critical value $\chi^2_{17df} = 27.59$; 5% level). Thus, the single equation logit model was considered adequate for the analysis.[2]

PDA/Handheld GPS Device Adoption

Significant explanatory variables and adoption odds. Results suggest that a younger farmer (*LOGAGE*) who used a computer in farm management and had a positive perception of Extension was more likely to adopt a PDA/handheld GPS device (Table 4). With respect to age, the odds of a cotton producer using a PDA/handheld GPS device was about 12% higher ($100 \times [e^{-1.2544\times(3.90-3.80)} - 1]$) for an adopter with an average age of 44.59 years when compared with a nonadopter with an average age of 49.57 years, holding all other variables constant (Table 3). In addition, a farmer who used a computer for farm management (*COM*) was 1.9 times more likely than others to use a PDA/handheld GPS device. Finally, a cotton producer who had a positive perception about the usefulness of information provided by Extension in making precision farming decisions (*EXTEN*) was about 84% ($100 \times [e^{0.60893} - 1]$) more likely to use a PDA/handheld GPS device. Thus, precision farming education programs directed by Extension may have had a positive influence on the probability of a farmer being a user of a PDA/handheld GPS device.

Farmer perceptions of yield variability (*YVAR*) in cotton fields was also positively associated with the use of PDA/handheld GPS devices (Table 4). Results indicate that a one standard deviation increase in perceived yield variability (249 lb/acre; Table 1) increased the odds of a cotton producer being a PDA/handheld device user by 45% ($100 \times [e^{0.00148 \times 249.41} - 1]$). None of the other explanatory variables describing characteristics of the farmer or the farm operation, such as farm size and education, were statistically significant (Table 4).

Several explanatory variables describing farmers' use of other technologies and services that may complement PDA/handheld GPS devices had significant and positive effects on the probability of a farmer adopting the technology (Table 4). For cotton producers who reported using remote sensing (*RS*) technology, the odds of also using a PDA/handheld device increased by a factor of 2.4, holding all other variables constant. In addition, the likelihood of being an adopter of a PDA/handheld GPS device and a user of in-field decision support software (*COTMAN*) was 5.7 times more likely than for a producer who did not use it. Thus, the results suggest that a farmer's use of decision support software and remotely sensed imagery might have been an important part of the technology package that included PDA/handheld GPS devices. Producers may use decision support software to track the stage of cotton plant growth and development and to time the application of in-season inputs such as plant growth regulators, insecticides, and harvest aids (boll openers, defoliants, and desiccants used to prepare the crop for harvest) (Bourland, Oosterhuis, and Tugwell, 1992). Remotely sensed imagery collected at regular intervals during the growing season and related to current crop status using plant mapping data can facilitate in-season VRT decisions. Thus, the decision support software combined with a PDA/handheld GPS device might have been used by adopters for ground truthing remote

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[2] Differences in the response rate by state in the survey may have produced a response bias given the 10% response rate. Post-stratification of the sample using the total number of responses in each state divided by number of farmers in the sample frame in each state did not reveal differences in the estimated parameters or standard errors. Thus, the unweighted logit model results are reported in Table 4.

Table 4. Logistic Regression Results of the PDA/Handheld GPS Adoption Analysis[a]

Independent Variable[b]	Coefficient[c]	Odds Ratio
Constant	−0.18500	NA
Farmer Characteristics		
LOGAGE	−1.25440*	0.285
EDUC	−0.03139	0.969
COM	0.65031*	1.916
EXTEN	0.60893**	1.838
Farm Characteristics		
ACRES	0.15788	1.171
OCROPS	−0.16985	0.844
LIVEST	0.13753	1.147
LANDTEN	0.00034	1.000
YVAR	0.00148**	1.001
INCOME	0.30196	1.353
Information Technologies		
RS	0.85539**	2.352
COTMAN	1.74900**	5.749
YM	0.05844	1.060
SSM	0.14759	1.159
ZSS	−0.09550	0.909
GSS	0.86468**	2.374
Variable-Rate Application Decisions		
SELF	0.48067	1.617
CONSULT	0.77212	2.164
DEALER	0.31821	1.375
VRINSGR	1.55626**	4.741
VRHA	−0.36936	0.691
VRPKL	1.05911**	2.884
Location Variables		
*ERS*1	0.06628	1.069
*ERS*5	−0.28649	0.751
*ERS*7	−0.03434	0.966
*ERS*9	0.39138	1.479
N	765	
Unrestricted Log-likelihood	−185.547	
Restricted Log-likelihood	−270.989	
Likelihood ratio statistic[d]	170.884**	
χ^2 statistic[e]	38.885**	
Correctly predicted	701(92%)	

[a] Dependent variable *PDA* = 1 if a personal digital assistant or handheld GPS device, 0 otherwise.

[b] Independent variables are defined in Tables 1 and 2.

[c] Significance at the 5% and 10% levels denoted by ** and * respectively.

[d] Likelihood ratio statistic is LR = 2 (log-likelihood unrestricted − log-likelihood restricted).

[e] 26 degrees of freedom at a 5% level of significance.

sensing data to verify problems and identify areas requiring treatment in cotton fields (Robinson, 2006). Another potential complementary technology that could be a source of ground truthing information is yield monitor data but it was not statistically significant in the logit model. Yield monitor data are collected annually at harvest and may not be as useful as remotely sensed imagery when combined with a PDA/handheld GPS device for tactical site-specific management of the growing cotton crop.

Results suggest that VRT application of insecticides and plant growth regulators (*VRINSGR*) was positively correlated with the use of a PDA/handheld GPS device (Table 4). A cotton producer in the sample who made *VRINSGR* applications was 4.7 times more likely to use a PDA/handheld GPS device than those who did not make *VRINSGR* applications. By comparison, the decision to make harvest aid applications using VRT (*VRHA*) was not significantly associated with the use of a PDA/handheld GPS device. VRT harvest aid decisions are primarily made on the basis of crop biomass in different sections of the field (Yang et al., 2003). Higher (lower) rates are applied on the areas of the field that have more (less) crop biomass. Thus, ground truthing using a PDA/handheld GPS device for VRT harvest aid decisions may not have been as important as for other VRT decisions for cotton producers in the sample.

Results also indicate that grid soil sampling (GSS) and VRT application of phosphorous, potassium, and lime (*VRPKL*) had a positive and significant impact on the adoption of PDA/handheld GPS devices and thus also may have been complementary technologies for farmers in the sample (Table 4). Holding all other variables constant, the odds of being a user of a PDA/handheld GPS device increases by 2.4 times for a producer also using *GSS* in their cotton fields. The other spatial soil information technologies (*SSM* and *ZSS*) were not associated with a greater likelihood of using PDA/handheld GPS devices. *GSS* data may have been more conducive for ground truthing using a PDA/handheld GPS device than SSM and ZSS information. In addition, a farmer who made *VRPKL* applications was 2.9 times more likely to be a user of a PDA/handheld GPS device than one who did not make *VRPKL* applications.

Probability Sensitivity Analysis. The sensitivity of the probability a farmer in the sample used a PDA/handheld GPS device with other complementary technologies was evaluated using the regression coefficients (Table 4). For the purpose of calculating probabilities, the nonsignificant variables were set equal to zero, farmer age (*LOGAGE*) and spatial yield variability (*YVAR*) were set to their mean values (Table 1), and the value of computer used for farm management (*COM*) was set equal to one. For the first scenario, $RS = 1$, $COTMAN = 1$, and $VRINSPGR = 1$ were assumed to represent a farmer in the sample who used remote sensing and plant mapping and made variable rate insecticide and plant growth regulator applications. The other significant explanatory variables were set equal to zero. A typical cotton farmer with these characteristics had a 58% probability of being a user of a PDA/handheld GPS device. Given $RS = 1$, $COTMAN = 1$, and $VRINSPGR = 1$, the probability of a producer being a user of a PDA/handheld GPS device increased to 72% if a farmer had a positive perception about the usefulness of Extension information for making precision farming decisions ($EXTEN = 1$).

The second scenario assumed that all of the aforementioned significant dummy variables were set equal to one, except *EXTEN*, which was set to zero. *GSS* and *VRPKL* were also set to one. Thus, the second case represented a cotton farmer who practiced grid soil sampling and variable rate application of phosphorous, potassium, and lime in addition to using *RS*, *COTMAN*, and *VRINSGR*. A producer with these attributes had a 90% probability of using a PDA/handheld GPS device. Similar to the first scenario, the probability of a producer being a user of a PDA/handheld GPS device increased to 95% if the farmer had a positive perception about the usefulness of Extension in making precision farming decisions ($EXTEN = 1$). The results from the logit model suggest that a farmer in the sample who used the aforementioned technologies for crop management may have been more able to exploit fully the productivity enhancing potential of PDA/handheld GPS devices.

As indicated by the coefficients for *EXTEN* and *COTMAN*, programs from Extension may also have been an important part of that technology package for farmers in the sample. A producer with these characteristics was 8.78 times [$e^{(-0.185+0.60893 \times 1+1.749 \times 1)} = 8.78$] more likely to have used a PDA/handheld GPS device than a grower who was not in these categories. The COTMAN decision support program was funded by Cotton Incorporated, a producer financed organization to promote cotton in the United States, and developed and supported by research and Extension personnel at the University of Arkansas and several other universities (Cochran et al., 1998; Texas A&M System, Texas AgriLife Extension). In addition, Cotton Incorporated sponsors regular workshops where Extension and research personnel train farmers and consultants about COTMAN as an in-field decision aid (Roberts et al., 2005).

Summary and Conclusions

Farmer decisions about the adoption of PDA/handheld GPS devices in precision cotton production were analyzed using a random utility model. The results of the logistic regression suggest that younger farmers who reported greater spatial yield variability were more likely to adopt a PDA/handheld GPS device for use in precision cotton production. The use of computers in farm management, remotely sensed images, plant mapping, grid soil sampling, and variable-rate application of selected inputs also positively influenced the probability of adoption. These results highlight the significance of the complementary relationships between PDA/handheld GPS device use and other precision farming technologies and practices. Mean comparisons of farm and farmer characteristics also demonstrated significant differences between adopters and nonadopters. Analysis of the use of PDA/handheld GPS devices in making variable rate decisions demonstrated the importance of these devices in different precision farming activities as well as which technologies most likely complement PDA/handheld GPS devices.

While the reader is urged to use caution as to inferences to the entire population of cotton producers in the Southeast due to the relatively low response rate, these in-sample findings may have implications for Extension and agribusiness firms involved in developing programs to assist in the promotion and implementation of precision farming practices. An understanding of the factors motivating adoption of a PDA/handheld GPS device in precision cotton production provides insight into areas of potential improvement in the promotion of precision agriculture. An understanding of the complementary precision agricultural tools and practices that motivate adoption also has the potential to illuminate areas where further product development could increase the efficiency of these products in a package of technologies. Finally, the results of this research documented the potential importance of programs and products (i.e., the COTMAN decision support program) from land grant universities and Extension in the adoption of PDA/handheld GPS devices by cotton farmers.

Insight into the complementarity of precision agriculture technology in particular warrants further research as producers oftentimes purchase technologies in bundles. To the extent that technology packages may be a product of farm dealership and implement marketing strategies, "technology bundles" will continue to become more commonplace in the manager's toolbox as costs decrease and producers more frequently have the necessary skills to manage these devices. For example, GPS systems and built-in yield monitors are typical accessories in today's combines. More accurate soil samples can be made with on-the-go hand-held GPS devices. Future studies investigating the simultaneous adoption of precision farming technology bundles, including PDAs, could analyze the extent to which adoption decisions are correlated using multivariate probit regression, or other systems approaches.

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