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Variable-Rate Application on Fertilizer Use in Cotton Production

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Abstract

Precision agriculture technologies are increasingly important in cotton production because input prices continue to rise. Farmers increase input efficiency using precision agriculture technologies by adjusting inputs to match soil fertility and plant nutrition requirements. This research examines the factors affecting changes in fertilizer use following variable-rate fertilizer application in cotton production. Data from a 2009 survey of cotton producers in 12 states of the United States were used in the analysis. Farmers who used precision soil sampling, planted larger cotton area, relied on other farmers for information about PA, grew picker cotton, and had higher household income were more likely to decrease fertilizer application with VRT. Results from this analysis are useful to farmers and policy makers interested in reducing fertilizer use in the face of rising fertilizer prices and growing concerns about the environmental impacts of farming.

Keywords: fertilizer-use changes, precision agriculture, probit regression, variable-rate technology

1. Introduction

As a high-value, high-input crop, cotton provides opportunities for farmers to increase profit, use inputs more efficiently, and reduce environmental impacts by using precision agriculture (PA) technologies to apply inputs at variable rates. The average value of cotton production in the United States for 2017 was \$1575 ha^{-1}, compared with \$1532 ha^{-1}, \$1121 ha^{-1}, and \$708 ha^{-1} for corn, soybean, and wheat, respectively (USDA-ERS, 2018a). Average operating cost of producing cotton was much higher at \$1047 ha^{-1}, compared with \$833 ha^{-1}, \$393 ha^{-1}, and \$264 ha^{-1} for corn, soybean, and wheat, respectively (USDA-ERS, 2018a). Average fertilizer costs for cotton were \$139 ha^{-1}, second only to \$288 ha^{-1} for corn among these crops (USDA-ERS, 2018a). Prices of fertilizer used in cotton production have increased by 225% between 1999 and 2016 (USDA-ERS, 2018b). To manage rising input costs, cotton farmers have stepped up efforts to increase input productivity by reevaluating current production practices as well as adopting advanced technologies such as PA.

The main components of PA include collecting field-level data about spatial variability in yields and crop needs, linking that information to specific locations in fields, and using the spatial information to manage input application (National Research Council, 1997; Swinton & Lowenberg-DeBoer, 1998). Application of inputs with VRT is the culminating element of PA. Nutrient management with PA technologies fits into the broader context of *precision conservation* (Berry et al., 2003, 2005). Berry et al. (2003, 2005) define precision conservation to include using “new spatial technologies to link a system from a site specific location, to a field, to a set of fields (farm) to a regional scale” (Berry et al., 2005, p. 363), the results of which are “directed to implement conservation management practices” (Berry et al., 2003, p. 332). McConnell and Burger (2011) demonstrate how PA technologies help producers make optimal decisions about the tradeoffs between profit maximization and conservation objectives in support of precision conservation efforts. An example of a regional nutrient management program is the Mississippi River Basin Healthy Watersheds Initiative (MRBI) that includes the cotton producing states of Arkansas, Louisiana, Mississippi, Missouri, and Tennessee (USDA-NRCS, 2018a). USDA NRCS has promoted the use of PA technology in the MRBI to management fertilizer more efficiently in farm fields through incentive payments from the Environmental Quality Incentives Program (USDA-NRCS, 2018b). The environmental benefits of PA are increasingly recognized by federal agencies promoting the adoption of best management practices because agriculture remains a significant source of non-point pollution (U.S. Environmental Protection Agency, 2009).

Research finds that PA technologies are more likely profitable in fields exhibiting high spatial variability, or when the crops grown are high-value or input-intensive (Swinton & Lowenberg-DeBoer, 1998). The soils on which cotton is typically grown in the Southern United States exhibit considerable variability and are conducive to management using PA technologies (Larson et al., 2008; Torbett et al., 2007, 2008). Applying inputs according to crop and/or soil needs using PA technologies may lead to increased input-use efficiency in fields with extensive variability (Roberts et al., 2004). As a result, farmers can increase profit margins with higher yields, lower input use, or both, and generate environmental benefits (Babcock & Pautsch, 1998; Batte, 2000; English et al., 2001; Khosla et al., 2002; Kitchen et al., 2005; Lal et al., 2011; Larkin et al., 2005; Lerch et al., 2005; McConnell & Burger, 2011; Roberts et al., 2000).

Changes in fertilizer use are difficult to generalize across the population of cotton growers using VRT technologies. Farm-level or field-specific data measuring fertilizer rate changes following VRT management are typically absent, but farm-level directional changes in fertilizer use (*e.g.*, increase, decrease, or no change) provide a way to assess the overall effects of VRT on fertilizer use across a population of adopters. A number of studies have evaluated farmer adoption of PA technologies such as VRT including Borghi et al. (2016), Paustian and Theuvsen (2017), Roberts et al. (2004), Robertson et al. (2012), and Zhou et al. (2017). However, relatively few studies have evaluated the relationship between PA technologies and fertilizer use. Khanna (2001) evaluated the determinants of nitrogen productivity following the adoption of site-specific soil testing and VRT input management. College education was the only variable associated with nitrogen productivity, suggesting that other unobserved factors such as soil quality influenced differences in input productivity. Torbett et al. (2007, 2008) evaluated the factors influencing farmer perceptions of the importance of PA technologies in reducing nitrogen (N), phosphorus (P), and potassium (K) use in cotton production. Farmers who used yield monitors, management zone soil sampling, grid soil sampling, and on-the-go sensing were more likely to rate highly the importance of PA technologies in reducing N, P, and K use. Older farmers who used computers for farm management and rented larger portions of the land they farmed were also more likely to rank highly the use of PA technology to reduce N, P, and K use in cotton production.

This research analyzes the factors associated with changes in fertilizer use following adoption of variable-rate technology (VRT) management of fertilizer application in cotton production. Our study contributes to the aforementioned literature by determining factors affecting changes in fertilizer use with VRT that were observed by cotton farmers in the United States. Recent advances in VRT fertilizer management in cotton production include optical sensing measurements. These technologies provide real-time data to producers such that they can adjust applied fertilizer. Stefanini et al. (2016) evaluated optical sensing based VRT fertilizer management on 21 farm fields in the MRBI states of Louisiana, Mississippi, Missouri, and Tennessee. They found four fields required less N, four fields required more N, and the remaining had no change when compared to the existing farmer practice. The methods applied here could be used to analyze these qualitative changes observed by farmers, conditional on farm, farmer, and farm business characteristics.

2. Data and Methods

2.1 Data

This study uses data from a 2009 survey of cotton producers in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, Missouri, North Carolina, South Carolina, Tennessee, Texas, and Virginia (Mooney et al., 2010). The survey was part of series of four surveys conducted in 2001, 2005, 2009, and 2013 to assess adoption of PA technologies by cotton farmers (Roberts et al., 2002; Cochran et al., 2006; Mooney et al., 2010; Zhou et al., 2015). The 2009 survey collected information about cotton-producer use of PA technologies, producer characteristics, and farm operation attributes. A question was asked about changes in the use of fertilizer, lime, seed, chemicals, and irrigation water after using VRT: "*Did your input use change for the following inputs after you used variable rate technology on your cotton fields? Mark a '+' for an increase, '-' for a decrease, or 'NC' for no change.*" Data from the subsequent 2013 survey were not used because a similar question was not asked. Information from the 2009 survey provides valuable insights into cotton farmer's observations of changes in fertilizer use with VRT. Variable rate application of inputs is increasingly important in cotton production with 25% of farmers using VRT in 2013 (Zhou et al., 2017).

Surveys were sent to 14,089 cotton producers based on the 2007-2008 marketing year lists of the Cotton Board in Memphis, TN, following the general mail survey procedures of Dillman (2000). The total number of cotton producers surveyed was 13,579, after excluding 306 undeliverable surveys and 204 respondents who had retired or no longer farmed cotton, for an overall response rate of 12.5% (1,692 surveys). The fertilizer component of the change in input question received 163 responses.

A comparison of the survey respondents with the USDA's 2007 Agricultural Census (USDA-NASS, 2007) indicates that the distribution of respondents is skewed towards larger cotton farms. Post-stratification survey weights were developed to account for this discrepancy following Lambert et al. (2014). The weighting procedure attends to potential non-response bias attributable to differences between large and small farms. The post-stratification weights do not correct for non-response bias; non-response bias relates to non-respondents being different in a way that affects the results specific to this study. The post-stratification weights calibrate the survey data such that the measures of central tendency characterizing the respondents approximate the distribution of cotton producers enumerated by the 2007 Agricultural Census (Lohr, 2010), improving the representativeness of the survey sample.

Secondary data for county differences in the number of farm input suppliers were combined with the primary survey data. Information about these businesses was based on the North American Industry Classification System (NAICS) codes 423820 and 424910 identifying "Farm and Garden Machinery and Equipment Merchant Wholesalers" and "Farm Supplier Merchant Wholesalers", respectively (U.S. Department of Commerce, 2018). The business establishment data are from the Census Bureau's 2007 County Business Patterns (U.S. Department of Commerce, 2018).

2.1 Statistical Methods

Three separate probit models were estimated because the outcome variables are mutually exclusive, respondents only reported their observations once, and the outcomes in fertilizer use (increase, decrease, or no change) are generated by states of nature given VRT management of fertilizer. In other words, whether fertilizer use increases, decreases, or is unchanged after VRT management is not a choice made by the farmer. Observational models were specified as:

$$F_{i,j} = \beta_j' X_i + \varepsilon_{i,j} \tag{1}$$

where, F equals 1 if farmer i reported change j (1 = increase, 2 = decrease, or 3 = no change) in fertilizer use (zero otherwise); X is a vector of observable exogenous covariates hypothesized to explain these changes; β is a vector of unknown parameters associated with the covariates; and ε is an independently and identically distributed error term with a zero mean and constant variance.

The dependent variable of Model 1 ("increase") was defined as $F_{i,1} = 1$ if farmer i increased fertilizer use, and zero otherwise (*i.e.*, input use decreased or did not change). Models 2 ("decrease") and 3 ("no change") were similarly defined with the appropriate indicators. In addition to the different site-specific information technologies used by cotton farmers, changes in fertilizer use following VRT input management were hypothesized to be influenced by the characteristics of the farm decision maker and attributes of the farm operation.

The empirical models were specified as:

$$\begin{aligned} F_{i,j} = {} & \alpha_j + \beta_{1j} SS_i + \beta_{2j} EC_i + \beta_{3j} SM_i + \beta_{4j} AE_i + \beta_{5j} ST_i + \beta_{6j} YM_i + \beta_{7j} AGE_i + \beta_{8j} EDUC_i \\ & + \beta_{9j} INC_i + \beta_{10j} INCF_i + \beta_{11j} LP_i + \beta_{12j} FD_i + \beta_{13j} CC_i + \beta_{14j} OF_i + \beta_{15j} EX_i + \beta_{16j} TS_i \\ & + \beta_{17j} IT_i + \beta_{18j} MD_i + \beta_{19j} FS_i + \beta_{20j} CA_i + \beta_{21j} OR_i + \beta_{22j} IR_i + \beta_{23j} PK_i + \varepsilon_{i,j} \end{aligned} \tag{2}$$

where, β_{kj} is a parameter determining the relationship between the kth covariate (k = 1 to 23) and outcome alternative j (1 = increase, 2 = decrease, 3 = no change). Covariates used in equation (2) are described in Table 1 and discussed below.

2.2 Key Hypotheses

Three key hypotheses are tested for each model. The null hypothesis of the first test is $\boldsymbol{\beta}_j = 0$. Rejection of this joint hypothesis suggests that the covariates included in the model explain the variability observed in the directional-change variable.

The second hypothesis is that the operator and farm business characteristics are unimportant in explaining observed changes in fertilizer application rates with VRT management. The null hypothesis for this case is $\beta_{7j} = \beta_{8j} = \beta_{9j} \ldots \beta_{23j} = 0$. Failure to reject the null hypothesis suggests that operator and farm business characteristics do not explain changes in fertilizer application rates. Rejection of the null hypotheses suggests that other factors (for example, management skills of the farm operator) influence changes in fertilizer use, conditional on the data generated by the site-specific information technologies.

The final set of hypotheses tests the significance of each covariate *k* separately (*i.e.*, $\beta_{kj} = 0$). The covariates representing site-specific information technologies, farm operator characteristics, and farm operation attributes are discussed below.

2.2.1 Site-Specific Information Technologies

Grid and management zone soil sampling (*SS*) directly provide information about soil fertility for generating VRT fertilizer application maps (Ferguson & Hergert, 2009; Lambert et al., 2014). Grid and zone soil sampling have been available to cotton farmers for much longer than other site-specific information technologies such as yield monitoring, which was not available for sufficiently accurate cotton yield monitoring until 2000 (Walton et al., 2008).

Table 1. Variable names, definitions and means for changes in fertilizer use following variable rate technology fertilizer management (n = 163)

Variable	Definition	Mean	Weighted mean
Dependent variables:			
INCREASE	Farmer reported fertilizer use increased (yes=1; else=0)	0.29	0.31
DECREASE	Farmer reported fertilizer use decreased (yes=1; else=0)	0.53	0.46
NO CHANGE	Farmer reported no change in fertilizer use (yes=1; else=0)	0.18	0.23
Independent variables:			
Information technologies			
SS	Farmer used grid and/or zone soil sampling (yes=1; else=0)	0.71	0.66
EC	Farmer used electrical conductivity (yes=1; else=0)	0.17	0.18
SM	Farmer used soil survey maps (yes=1; else=0)	0.15	0.13
AE	Farmer used aerial photos (yes=1; else=0)	0.12	0.09
ST	Farmer used satellite images (yes=1; else=0)	0.09	0.08
YM	Farmer used a yield monitor (yes=1; else=0)	0.28	0.22
Producer characteristics			
AGE	Age of the primary decision maker (in 10 years)	5.06	5.13
EDUC	Farmer held a Bachelor's or higher degree (yes=1; else=0)	0.55	0.51
INC	Household income over $100,000 (yes=1; else=0)	0.53	0.49
INCF	Proportion of household income from farming	0.76	0.71
LP	Farmer used a laptop or handheld computer in the field (yes=1; else=0)	0.28	0.24
FD	Farmer used farm dealers for precision agriculture information (yes=1; else=0)	0.77	0.73
CC	Farmer used crop consultants for precision agriculture information (yes=1; else=0)	0.50	0.47
OF	Farmer used other farmers for precision agriculture information (yes=1; else=0)	0.66	0.64
EX	Farmer used University Extension for precision agriculture information (yes=1; else=0)	0.55	0.53
TS	Farmer used trade shows for precision agriculture information (yes=1; else=0)	0.48	0.45
IT	Farmer used the internet for precision agriculture information (yes=1; else=0)	0.36	0.35
MD	Farmer used news or media for precision agriculture information (yes=1; else=0)	0.39	0.41
FS	Number of farm input suppliers in the county	7.23	7.75
Farm operation characteristics			
CA	Total cotton area farmed (in 405 hectare units)	1.04	0.77
OR	Percentage of cotton area owned	0.32	0.36
IR	Farmer used irrigation (yes=1; else=0)	0.59	0.61
PK	Farmer used picker harvest technology (yes=1; else=0)	0.82	0.80

Thus, grid and zone soil sampling for cotton farmers served as the typical entry technology into PA as opposed to yield monitoring with other crops (Lowenberg-DeBoer, 1999; Walton et al., 2008). Therefore, cotton farmers are likely to be more familiar with the data and the usefulness of this information in evaluating changes in fertilizer use following the adoption of VRT. Torbett et al. (2007, 2008) found that farmers who used grid or zone soil sampling ranked more highly the importance of PA in reducing N, P, and K use in cotton production. Given the Torbett et al. (2007, 2008) findings and that farmers typically move from whole-field application based on a yield goal to a grid- or zone-based fertilizer plan, those who adopt this site-specific information technology will more likely reduce fertilizer use with VRT management.

Electrical conductivity (*EC*) is an information technology that can be used to generate data for VRT fertilizer management based on soil depth and texture (*i.e.*, the proportions of sand, silt, and clay in the soil) (Grisso et al., 2009). This technology also can be used to improve the accuracy of soil boundaries in soil maps, delineate soil management zones, and for directed soil sampling (Grisso et al., 2009). Electrical conductivity as a tool to determine a VRT fertilizer management plan is still often misunderstood or misinterpreted given the various soil properties determining it (Corwin & Lesch, 2003). Therefore, predictions about the effects of electrical conductivity on directional changes in fertilizer use are difficult to anticipate.

Several other site-specific information technologies, soil maps (*SM*), aerial photos (*AE*), satellite imagery (*ST*), and yield monitors (*YM*), may also influence changes in fertilizer use. As with grid or zone soil sampling, Torbett et al. (2007, 2008) found that cotton farmers who used these technologies ranked more highly the importance of PA in reducing N, P, and K use. Nevertheless, a priori predictions about their effects on fertilizer use were difficult given that the data provided by these technologies have less of a direct link to the VRT fertilizer management plan compared to grid or management zone soil sampling.

2.2.2 Farm Operator Characteristics

The influence of operator age (*AGE*) on observed changes in fertilizer use following VRT management was hypothesized to be positive. Older farmers may have the knowledge and experience necessary to better recognize a change in fertilizer use, regardless of whether it is an increase or a decrease. In contrast, older farmers tend to be more risk averse due to shorter planning horizons, and therefore invest in a technology such as VRT only if they anticipate a reduction in input use and cost. For this reason, older farmers who choose to invest in VRT were expected to decrease fertilizer use.

Farmers with Bachelor's degrees or higher (*EDUC*) were hypothesized to be more likely to report an impact of VRT on fertilizer use. Farmers with a college degree were expected to have the analytical skills to manage site-specific information for VRT application of fertilizer better and be more likely to recognize changes in fertilizer use (Torbett et al., 2007, 2008) and, thus, experience changes in fertilizer use (*e.g.*, increase, decrease).

Farm household income (*INC*) entered the models as a dummy variable, with \$100,000 used as a threshold. This threshold was selected based on the approximate median household income of U.S. cotton farmers (USDA ERS, 2018). Higher income provides the financial ability to invest in higher rates of fertilizer application if this is the course of action suggested by the information collected using PA site-specific technologies (Walton et al., 2008; Napier et al., 2000). Therefore, farmers with household incomes over \$100,000 were expected to increase fertilizer use with VRT.

Farmers with higher percentages of household income from farming (*INCF*) were expected to increase fertilizer use with VRT. Full-time farmers may be more risk averse than part-time farmers who are partially supported by off-farm income sources (Evans & Ngau, 1991). Risk-averse farmers also may be more likely to over apply fertilizer as insurance against crop loss (Babcock, 1992). Therefore, full-time farmers may use PA technologies as tools to increase fertilizer productivity, rather than reducing its use, and may be more likely to increase fertilizer use with VRT management.

Farmers using laptops or handheld computers in the field (*LP*) were hypothesized to observe changes in fertilizer use with VRT management, but the direction of the change was unclear (increase, decrease, or no change). The use of these devices allows farmers to verify and enhance the accuracy of data collected using site-specific information technologies, leading to more accurate estimation of the connections between those technologies, VRT management plans, and fertilizer use (Walton et al., 2010).

Information sources include farm dealers (*FD*), crop consultants (*CC*), university extension (*EX*), other farmers (*OF*), trade shows (*TS*), the internet (*IT*), and news or media outlets (*MD*). How these information sources affect the acquisition and application of PA technologies to influence changes in fertilizer use may differ. The number of farm input suppliers in a county (*FS*) was included as another proxy for access to information about VRT. Therefore, *a priori* expectations were not made about the directional relationships these covariates would have on changes in fertilizer use.

2.2.3 Farm Operation Attributes

Cotton area farmed (*CA*) was hypothesized to be associated with changes in fertilizer use. Larger operations are more likely to face managerial challenges posed by field fertility heterogeneity, and therefore more likely to experience changes in fertilizer use from VRT input management (Roberts et al., 2004; Torbett et al., 2007; Walton et al., 2010).

The effect of the percentage of total cotton area owned (*OR*) on changes in fertilizer use with VRT management was difficult hypothesize *a priori*. On the one hand, farmers owning relatively more of the cotton land they operate are likely more familiar with the historical fertilizer requirements of their owned fields (Torbett et al., 2007). For this reason, farmers who own more of the land they farm may be more likely to recognize changes in fertilizer use from VRT regardless of magnitude or direction. On the other hand, P and K applications are investments in soil productivity that may not be realized in the application year. Before adopting VRT fertilizer management, producers may have already corrected or partially corrected spatial P and K imbalances in their owned fields through whole-field applications. On rented fields, the risk of losing their investment in future soil productivity may have discouraged producers from correcting nutrient imbalances. For these reasons, producers owning larger proportions of farmed cotton area may be less likely to change (increase, decrease) fertilizer use and more likely not to change fertilizer use than those with smaller proportions of owned cotton land.

Cotton farmers using irrigation technology (*IR*) were hypothesized to increase fertilizer use with VRT. Previous research established the interaction between irrigation water and other inputs, particularly fertilizer (Roberts et al., 2006). Irrigated cotton is generally associated with higher yields, but also has higher input requirements than dryland cotton (Larson et al., 2008). When irrigation systems are used, farmers are expected to increase fertilizer use following VRT management, given they may associate higher productivity with higher input use.

Harvest technology used by cotton farmers (*i.e.*, picker vs. stripper) may influence changes in fertilizer use. As a proxy for location and production techniques, the use of picker harvest technology (*PK*) was hypothesized to decrease fertilizer use with VRT management. Over-application of fertilizer can reduce cotton yield and fiber quality by shifting development away from cotton boll development towards vegetative growth (Kohli and Morrill, 1976; Gaylor et al., 1983; Howard et al., 2001). For this reason, farmers growing higher-valued picker cotton often avoid excess fertilizer application to prevent discounts for lint quality. Additionally, better fertilizer management reduces the need for greater quantities of plant growth regulators and harvest aids used to counterbalance excessive vegetative growth prior to harvest (Fritschi et al., 2003). Therefore, producers using picker harvest technology may experience an overall decline in fertilizer use with VRT management compared to those using stripper harvest technology.

2.3 Estimation Methods

The probit regression models were estimated with quasi-maximum likelihood (Greene, 2011). Standard errors were estimated with heteroskedastic-robust covariance estimators adjusted with the survey weights (Cameron & Trivedi, 2005). The hypotheses were tested using Wald statistics. The marginal effect of a continuous variable was calculated by differentiating the probability that a respondent experienced change *j* with respect to covariate x_k:

$$\frac{\partial \Pr(F_{i,j}=1|X)}{\partial x_k} = \frac{\partial \Phi_{F_{i,j}}}{\partial x_k} = \phi\left(\beta_j' X_i\right)\beta_{kj} \quad (3)$$

where, Φ and ϕ are the cumulative distribution function and probability density function of the standard normal distribution, respectively. The marginal effect for a binary variable was calculated as:

$$\Pr\left(F_{i,j}=1\middle|X, x_k=1\right) - \Pr\left(F_{i,j}=1\middle|X, x_k=0\right) \quad (4)$$

which is the difference in the probabilities of experiencing a given change in fertilizer use when covariate x_k equals 1 and 0.

Multicollinearity can affect the inferential power of tests by inflating the standard errors of the estimates (Greene, 2011). Condition indexes and proportions of variation were used to detect collinear relationships (Belsley et al., 1980). Proportions of variation above 0.5 for two or more explanatory variables accompanying a condition index greater than 30 indicate potential multicollinearity problems (Belsley et al., 1980).

3. Results and Discussion

3.1 Descriptive Statistics

Weighted and unweighted means of selected variables were evaluated (Table 1). Means of the weighted and unweighted data are similar, except for farm size. The post-stratification weights are based on cotton area farmed, and smaller farms in the survey sample are given relatively more weight, reducing the weighted average farm size from 421 ha to 312 ha. The following discussion of descriptive statistics focuses on the results of the weighted data. The differences identified here are initial estimates because the comparisons are made without holding other factors constant. The probit models in the next section provide comparisons that are unaffected by changes in other factors.

About 46% of respondents decreased fertilizer use with VRT management, less than a third (31%) increased fertilizer use, and 23% had no change in fertilizer use. Grid or zone soil sampling and yield monitoring were the most widely used site-specific information technologies with 66% and 22% of farmers using these technologies, respectively. The average age of farmers was 51 years and they earned 71% of household income from farming. Respondents grew an average cotton area of 312 ha, and 80% used picker harvest technology.

Differences in the proportional means among the VRT users having increased, decreased, or unchanged fertilizer use were compared using *t*-tests (Table 2). Farmers who decreased fertilizer use were more likely to use grid or zone soil sampling (79%) and yield monitors (29%) than farmers who had no change (56% and 18% respectively) or increased (53% and 13% respectively) fertilizer use. Respondents who decreased fertilizer use were more likely to use picker harvest technology (94%) than farmers who increased fertilizer use (57%). Farmers using VRT who had no change in fertilizer use were more likely to consult university Extension for information about PA technologies (83%) than farmers who increased (41%) or decreased (46%) fertilizer use.

3.2 Probit Regressions

The null hypotheses, $\boldsymbol{\beta}_j = 0$, was rejected for the fertilizer use increase and decrease models, suggesting that the covariates were important in explaining the variability across PA users and changes in fertilizer use due to VRT management (Table 3).

Table 2. Comparisons of characteristics among cotton farmers reporting directional changes in fertilizer use following variable rate fertilizer management

Variables[ab]	Perceived changes in fertilizer use		
	INCREASE	*DECREASE*	*NO CHANGE*
	Proportional means[cd]		
SS	0.53 a	0.79 b	0.56 a
YM	0.13 a	0.29 b	0.18 a
EX	0.41 a	0.46 a	0.83 b
PK	0.57 a	0.94 b	0.84 b
N	47	86	30
Expanded population[e]	488	735	360

Note. [a] Variables are defined in Table 1; [b] Only variables with proportional means that are statistically different for at least one observed category are included; [c] Proportions of farmers indicating the respective directional change in fertilizer use (*INCREASE*, *DECREASE*, *NO CHANGE*) also indicating use of the respective information technology (*SS*, *YM*), information source (*EX*), or harvest technology (*PK*); [d] Proportional means followed by the same letter in each row are not statistically different at the 0.05 probability level based on the results of *t*-tests; [e] The expanded population is the sum of post-stratified weights across observations.

The model for no change in fertilizer use failed to reject the null hypotheses, $\boldsymbol{\beta}_j = 0$, at the 10% significance level, suggesting that the model did not explain variation in the dependent variable. Condition indices were less than 30, indicating that the standard errors of the estimates were not affected by multicollinearity.

The null hypothesis that the site-specific information technologies were the only factors important for determining changes in fertilizer use, $\beta_{7j} = \beta_{8j} = \beta_{9j} \ldots \beta_{23j} = 0$, was rejected for both the increase and decrease models, implying that other factors play a role in determining changes in fertilizer use by VRT cotton producers (Table 3).

Results indicate that farmers who used soil sampling (*SS*) were 29% more likely to decrease fertilizer application with VRT management than those who did not use soil sampling. By comparison, farmers who used electrical conductivity (*EC*) were 27% less likely to decrease fertilizer use than other farmers, all other factors equal. Given that electrical conductivity measures soil properties associated with fertility, this finding appears to contradict the result for the reduction in fertilizer use for farmers using soil sampling. Previous research discussed the difficulty with interpreting electrical conductivity information, given it is determined by several soil properties such as soil salinity, soil texture, temperature and water content (Corwin & Lesch, 2003). As a result, electrical conductivity measures are often still misunderstood or misinterpreted (Corwin & Lesch, 2003), possibly explaining the unexpected effect of electrical conductivity on decreases in fertilizer use with VRT management. No other site-specific information technology had a significant impact on VRT users' fertilizer use.

These findings differ from Torbett et al. (2007, 2008) who found that yield monitors and soil maps also were associated with reduced fertilizer levels with PA.

The impacts of farm size (*CA*) on changes in fertilizer use were observed in both the fertilizer increase and fertilizer decrease models. The probability of a farmer increasing fertilizer use was reduced by 10% for each additional 405 ha of cotton area farmed. In addition, farmers had a 9% higher probability of decreasing fertilizer use for each additional 405 ha of cotton area farmed. These findings suggest that the potential for the higher spatial variability on larger cotton farms may allow farmers to reduce fertilizer use with VRT management.

Producers using VRT who relied on other farmers for information about PA were 23% more likely to decrease fertilizer use and 29% less likely to increase fertilizer use with VRT. If a farmer's neighbors found VRT to be a useful tool for reducing fertilizer costs, the farmer would be more likely to reduce fertilizer cost from using VRT, given the geographic proximity of the farms. These findings are consistent with Torbett et al. (2007, 2008) who found that the experience of other farmers was associated with farmers who ranked more highly the importance of PA in reducing N, P, and K use in cotton production.

Picker cotton producers using VRT were 37% more likely to decrease fertilizer use and 57% less likely to increase fertilizer use compared with producers using stripper harvest technology. Farmers growing higher-valued picker cotton may use VRT to moderate fertilizer application rates in sections of the field with higher soil fertility to avoid rank cotton with excess vegetation. Thus, VRT fertilizer management may reduce the potential for lint quality discounts at harvest and the need for greater quantities of plant growth regulators and harvest aids.

The two variables describing household income were associated with VRT users who increased fertilizer use (Table 3). Producers with higher household incomes (*INC* > $100,000) who earned relatively more income from farming (*INCF*) were more likely to increase fertilizer use after using VRT. Farmers using VRT with household income over $100,000 per year were 20% more likely to increase fertilizer use. Higher income may provide the financial ability to invest in higher levels of fertilizer application as prescribed by PA information. Effects of the proportion of income from farming were observed in both the fertilizer increase and fertilizer decrease models. Producers were 31% more likely to increase and 34% less likely to decrease in fertilizer use, given a 1% increase in the proportion of household income from farming. Farmers who relied on farming for a larger portion of their income may be more likely to over-apply fertilizers as insurance against crop loss regardless of the rate indicated by the site-specific information technologies (Babcock, 1992).

The negative marginal effect for the contribution of owned cotton area to total cotton area (*OR*) in the *INCREASE* model (Table 3) indicates that farmers were 26% less likely to increase fertilizer use for each 1% increase in the proportion of owned cotton area. This result supports the hypothesis that farmers may have already corrected or partially corrected nutrient imbalances in their owned fields before adopting VRT fertilizer management, but less so in rented fields where the benefits of investment in future soil productivity many not be fully realized. Although not significant at the 10% level, signs of the marginal effects in the *DECREASE* model (negative) and the *NO CHANGE* model (positive) also are in line with this hypothesis.

Table 3. Marginal effects of information technology and demographic factors influencing changes in fertilizer use following variable rate fertilizer management

Independent variable[b]	Marginal effects[a]		
	INCREASE[c]	*DECREASE*[c]	*NO CHANGE*[c]
SS	-0.092	0.288**	-0.175
EC	0.182	-0.274**	0.120
SM	0.003	0.081	-0.108
AE	0.211	-0.146	-0.019
ST	0.200	-0.015	-0.055
YM	-0.166	0.217	-0.038
AGE	0.001	0.019	-0.015
EDUC	-0.093	0.035	0.033
INC	0.201**	-0.096	-0.063
INCF	0.311**	-0.338*	0.016
LP	0.028	-0.014	-0.007
FD	0.110	-0.179	0.025
CC	-0.109	0.145	-0.029
OF	-0.285***	0.227**	0.034
EX	0.104	-0.381***	0.227***
TS	-0.093	0.018	0.049
IT	-0.063	-0.100	0.081
MD	-0.015	0.150	-0.077
FS	-0.003	-0.009	0.011**
CA	-0.099**	0.094*	0.000
OR	-0.264*	-0.027	0.173
IR	0.095	-0.036	-0.056
PK	-0.566***	0.374***	0.148
N	163	163	163
Expanded population[d]	1,583	1,583	1,583
Wald statistic hypothesis one[e]	50.46***	57.31***	24.13
Wald statistic hypothesis two[f]	41.56***	36.65***	22.52

Note. [a] *, **, and *** denote significance at the 0.10, 0.05, and 0.01 levels, respectively; [b] Explanatory variables are defined in Table 1; [c] *INCREASE* equals one if the farmer reported fertilizer use increased, zero otherwise; *DECREASE* equals one if the farmer reported fertilizer use decreased, zero otherwise; *NO CHANGE* equals one if the farmer reported fertilizer use did not change, zero otherwise; [d] The expanded population is the sum of post-stratified weights across observations; [e] Hypothesis one: $\boldsymbol{\beta}_j = 0$; [f] Hypothesis two: $\beta_{7j} = \beta_{8j} = \beta_{9j} \ldots \beta_{23j} = 0$.

Producers who used university Extension (*EX*) as a PA information source were 38% less likely to decrease fertilizer and 23% more likely have no change in fertilizer use with VRT management (Table 3). University Extension generates information for a wide range of farmers in a particular region as opposed to other sources of PA information that may provide a farmer with detailed information customized for their particular operation (Velandia et al., 2010; Jenkins et al., 2011). Thus, university Extension is often regarded as providing general, objective information (Larson et al., 2008; Jenkins et al., 2011). The perceived impartiality of university Extension may influence farmers to be more conservative in adjusting their fertilizer use with VRT.

4. Conclusions

This research contributes to the PA literature by examining the factors influencing directional changes in fertilizer use (*e.g.*, increase, decrease, or no change) following VRT input management. The factors influencing changes in fertilizer use experienced by cotton farmer were analyzed using probit regression. Findings suggest that farmers who used grid or management zone soil sampling, grew larger areas of cotton, used other farmers as a source of PA information, and grew picker cotton were more likely to reduce fertilizer use following VRT management. Results also suggest that higher income cotton farmers who earn a larger portion of income from farming were more likely increase fertilizer use with VRT management. In addition, farmers who owned relatively more of the cotton land they operated were less likely to increase fertilizer use and more likely not to change fertilizer use with VRT management.

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