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Simultaneous Adoption of Herbicide-Resistant and Conservation-Tillage Cotton Technologies

Roland K. Roberts, Burton C. English, Qi Gao, and James A. Larson

If adoption of herbicide-resistant seed and adoption of conservation-tillage practices are determined simultaneously, adoption of herbicide-resistant seed could indirectly reduce soil erosion and adoption of conservation-tillage practices could indirectly reduce residual herbicide use and increase farm profits. Our objective was to evaluate the relationship between these two technologies for Tennessee cotton production. Evidence from Bayes' theorem and a two-equation logit model suggested a simultaneous relationship. Mean elasticities for acres in herbicide-resistant seed with respect to the probability of adopting conservation-tillage practices and acres in conservation-tillage practices with respect to the probability of adopting herbicide-resistant seed were 1.74 and 0.24, respectively.

Key Words: Bayes' theorem, conservation tillage, cotton, genetically modified crops, herbicide-resistant crops, simultaneous logit model, technology adoption

JEL Classifications: Q12, Q16, Q24, O33

Herbicide-resistant BXN (Buctril-resistant) cotton seed was first introduced in 1995 by the Stoneville Pedigreed Seed Company (Ward et al. 1995) and Roundup-Ready cotton seed became commercially available in 1996 (Johnson 1996). The adoption of herbicide-resistant seed by farmers has dramatically changed cotton production practices with potential consequences for the environment. Monsanto claims that adoption of herbicide-resistant seed facilitates adoption of conservation tillage, which "sustains the environment." Soule, Tegene, and Wiebe used data from the 1996 USDA Agricultural Resource Management Survey (ARMS) and with logit analysis evaluated the effects of land tenure on adoption of conservation-tillage practices. Although data from the 1996 ARMS were available for adoption of herbicide-resistant crops (Fernandez-Cornejo and McBride 2002), adoption was low, and Soule, Tegene, and Wiebe were not intent on evaluating the synergy between adoption of herbide-resistant seed and conservation-tillage practices. Fernandez-Cornejo and McBride (2002) used 1997 ARMS data and a two-equation simultaneous probit model to evaluate this potential synergistic relationship. Contrary to Monsanto's claim, they found no evidence that soybean farmers who

Roland K. Roberts and Burton C. English are professors, James A. Larson is associate professor, and Qi Gao is former graduate research assistant, Department of Agricultural Economics, University of Tennessee, Knoxville, TN.

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had adopted herbicide-resistant seed had a higher probability of adopting no-tillage practices than farmers who had not adopted herbicide-resistant seed. They found evidence supporting the converse, however; farmers who had adopted no-tillage practices had a higher probability of adopting herbicide-resistant soybean seed than farmers who had not adopted no-tillage practices. Lack of simultaneity most likely resulted from using cross-sectional data for the year after herbicide-resistant soybean seed was first introduced, leaving little time for adjustment in tillage practices. Using data from a 1999 survey of cotton farmers conducted in South Georgia, Ward et al. (2002) found evidence based on efficiency measures that farmers may have incentive to simultaneously adopt herbicide-resistant seed and conservation-tillage practices. Marra, Piggott, and Sydorovych found that 76% of North Carolina corn, soybean, and cotton acreage in herbicide-resistant seed was produced with conservation-tillage practices in 2001, while only 64% of corn, soybean, and cotton acreage in conventional seed was produced with conservation-tillage practices. Their specific results for cotton were different, with these two percentages being about the same at close to 73%.

Findings from the aforementioned cross-sectional analyses suggest a simultaneous relationship may exist between adoption of herbicide-resistant seed and adoption of conservation-tillage practices, but the evidence is inconclusive, especially for cotton. Sufficient annual time-series data are now available to investigate the relationship of the adoption of these two technologies over time. The Conservation Tillage Information Center (Fawcett and Towery) used a limited time-series sample of percentages of acres in glyphosate-resistant crops by tillage method for 1998 through 2000 and a 2001 survey by the American Soybean Association to suggest a simultaneous relationship between adoption of glyphosate-resistant crops and conservation-tillage practices in the United States. The information for Tennessee cotton acreage in Figure 1 (Doane Marketing Research, Inc.; Monsanto; Tennessee Department of Agriculture, 1996–2003, 2004) also suggests a relationship between adoption of herbicide-resistant seed and conservation-tillage practices. From 1992 through 1998, the share of Tennessee cotton acreage in conservation-tillage practices averaged 38% with no discernable trend. In 1999 when adoption of herbicide-resistant cotton seed started in earnest, the share of conservation-tillage acreage began a slight upturn to 40% with a dramatic increase thereafter, averaging 76% between 2000 and 2004 and reaching almost 100% in 2003 and 2004. During the 1992 through 2004 period, cotton acreage in Tennessee showed no perceptible trend, except during the mid-to-late 1990s when the Boll Weevil Eradication Program was active in middle and southwestern Tennessee (Suarez, Larson, and English 2000). Because of eradication program costs, farmers had an incentive to switch to other crops during the active phase of the program. Cotton acreage was relatively stable after 1998, when herbicide-resistant seed and conservation-tillage practices were being rapidly adopted.

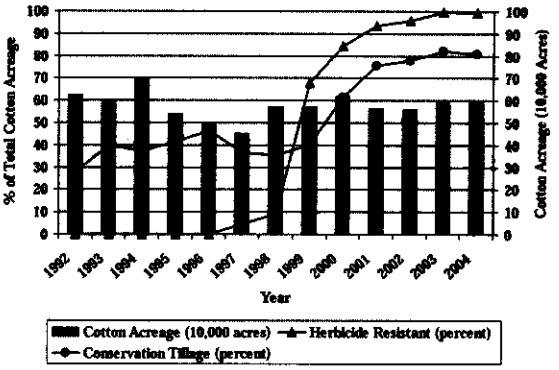

Figure 1. Total Tennessee cotton acreage with percentages in herbicide-resistant seed and conservation-tillage practices

In our research, annual time-series data along with Bayes' theorem and simultaneous estimation of two binomial logit models were used to examine the relationship between adoption of herbicide-resistant seed and adoption of conservation-tillage practices in Tennessee cotton production. If adoption of herbicide-resistant seed influenced adoption of conservation-tillage practices, adoption of herbicide-resistant seed may have indirectly led

to greater soil conservation and, if adoption of conservation-tillage practices influenced adoption of herbicide-resistant seed, adoption of conservation-tillage practices may have indirectly led to reduced residual herbicide use and increased farm profits as adoption of herbicide-resistant seed increased (Marra, Pardy, and Alston).

The choice of tillage method is a major decision for farmers because of its potential impacts on soil erosion and farm profit. Erosion of agricultural topsoils has been recognized as a problem for decades. Federal mandates have encouraged production practices to curb erosion. Anderson and Magleby and Heimlich provide a comprehensive overview of U.S. government policies designed to encourage conservation of our nation's topsoils. For example, Conservation Compliance, established in the 1985 Farm Bill, resulted in farms with highly erodible lands being required to alter cropping patterns and tillage practices to reduce erosion as a requirement for receiving government payments; in 1991, the Crop Residue Management Action Plan was developed to assist producers in implementing conservation systems. Tennessee has the most erodible cultivated cropland in the United States (Denton), with cotton being produced on some of those erodible soils. Adoption of conservation-tillage practices in cotton production has lagged behind adoption in other row crops (Tennessee Department of Agriculture 2004). Exploring the relationship between adoption of herbicide-resistant seed and adoption of conservation-tillage practices in Tennessee cotton production could lead to improved policies for reducing soil erosion.

Farmers who adopt conservation-tillage practices may benefit if adopting herbicide-resistant cotton seed allows them to use more effective herbicide treatment systems (Shoemaker et al.). Weed control is a vital component of conservation tillage. Failure to control weeds with conservation tillage can result in decreased quantity and quality of output. Besides preventing yield loss from weed competition, weed control is particularly important in cotton production because weeds can stain lint during harvest and processing, resulting in price discounts (Moore). Herbicide-resistant seed provides farmers with effective weed control programs that eliminate some problems associated with conservation programs (Fawcett and Towery). Investigating the relationship between adoption of conservation-tillage practices and herbicide-resistant seed could increase our understanding of ways to increase farm profit and reduce residual herbicide use (Marra, Pardey, and Alston) while conserving soil.

The objectives of this research were: (1) to evaluate the relationship between adoption of herbicide-resistant cotton seed and conservation-tillage cotton production practices over time and (2) to quantify the effects of economic phenomena on the adoption of herbicide-resistant seed and conservation-tillage practices for cotton production in Tennessee.

Methods and Data

The problem at hand is one of simultaneous adoption of synergistic technologies and management practices. Wu and Babcock used a polychotomous-choice selectivity model to evaluate choices among crop management plans, including tillage, rotation, and fertility management alternatives. Dorfman used a multinomial probit model, estimated in a Bayesian framework using Gibbs sampling (Geman and Geman), to evaluate adoption of improved irrigation methods and integrated pest management practices in apple production. Fernandez-Cornejo, Hendricks, and Mishra estimated a trivariate-choice selectivity model to evaluate the relationships among off-farm operator employment, off-farm spouse employment, and adoption of herbicide-resistant soybean seed. In an analysis more related to this article, Fernandez-Cornejo and McBride simultaneously estimated two binomial probit models for adoption of herbicide-resistant seed and no-tillage practices in soybean production.

Two methods were used to evaluate the relationship between adoption of herbicide-resistant cotton seed and conservation-tillage cotton production practices in Tennessee. The first method was a comparison of conditional

probabilities using Bayes' theorem (Render, Stair, and Hanna). The second was the simultaneous estimation of two binomial logit models, where the two equations represent the choices between adopting herbicide-resistant versus conventional seed and adopting conservation-tillage versus conventional tillage practices. Both methods assume the probability that a farmer will choose to produce an acre of cotton using a particular technology is equal to the share of cotton acreage produced with that technology.

Bayes' Theorem

Consider two events: (1) Event H occurs when an acre of Tennessee cotton is produced with herbicide-resistant seed and (2) Event C occurs when an acre of Tennessee cotton is produced with conservation-tillage practices. The complement of event H ($\bar{H}$) occurs when an acre is produced with conventional cotton seed and the complement of C ($\bar{C}$) occurs when an acre is produced with conventional tillage practices. Let the probability of an event occurring be represented by the share of total Tennessee cotton acreage in that event. When events H and C are not independent, Bayes' theorem states that the conditional probability of event H occurring given that event C has occurred, $P(H|C)$, is equal to the joint probability of events H and C occurring, $P(HC)$, divided by the marginal probability of event C occurring, $P(C)$, or mathematically (Render, Stair, and Hanna):

$$(1) \quad P(H|C) = \frac{P(HC)}{P(C)}.$$

If events H and C are independent, $P(H|C) = P(H)$ (Render, Stair, and Hanna). Bayes' theorem can be stated conversely as

$$(2) \quad P(C|H) = \frac{P(HC)}{P(H)},$$

where $P(C|H)$ is the conditional probability of event C occurring given that event H has occurred. If events H and C are independent, $P(C|H) = P(C)$.

Two other probabilities of interest are the conditional probability of one event occurring given that the complement of the other event has occurred

$$(3) \quad P(H|\bar{C}) = \frac{P(H\bar{C})}{P(\bar{C})} = \frac{P(H) - P(HC)}{1 - P(C)}, \text{ and}$$
$$P(C|\bar{H}) = \frac{P(\bar{H}C)}{P(\bar{H})} = \frac{P(C) - P(HC)}{1 - P(H)}.$$

When events H and C are independent, $P(H|\bar{C}) = P(H)$ and $P(C|\bar{H}) = P(C)$. Independence implies that the conditional probabilities in Equations (1) and (3) are equal, the conditional probabilities in Equations (2) and (4) are equal, and these conditional probabilities equal their respective marginal probabilities. Alternatively, if $P(H|C) > P(H|\bar{C})$, the adoption of conservation-tillage practices has increased the probability of adopting herbicide-resistant cotton seed, and if $P(C|H) > P(C|\bar{H})$, the adoption of herbicide-resistant seed has increased the probability of adopting conservation-tillage practices.

We calculated and compared the conditional probabilities in Equations (1) through (4) using data for 1998 through 2004 (Doane Marketing Research, Inc.) on the percentages of Tennessee cotton acres in herbicide-resistant seed, conservation-tillage practices, and in both technologies. This data set contained the only consistent time-series data found that included $P(C)$, $P(H)$, and $P(HC)$. Data were not available from Doane Marketing Research, Inc. for 1995 through 1997 and were excluded from the conditional probability analysis.

Logit Analysis

Following Garrod and Roberts, assume cotton production can be accomplished during a particular year using herbicide-resistant or conventional seed technologies and cotton acreage is constrained to a fixed level by exogenous or predetermined events (e.g., naïve price expectations and lagged cotton acreage). Let p_H and $p_{\bar{H}}$ represent average profit functions for herbicide-resistant and conventional seed technologies, respectively, where p_i is conditional upon the number of acres in technology i (q_i;

$i = H$ and $\bar{H}$), prices of outputs, and prices of inputs. Thus, we assume the farmer's problem is to allocate cotton acreage between herbicide-resistant and conventional seed technologies to achieve maximum profit. Our hypothesis is that adoption of herbicide-resistant seed is not independent of adoption of conservation-tillage practices. If they are not independent, p_i also includes conservation-tillage cotton acreage as an argument.

Assuming q_H and $q_{\bar{H}}$ are dependent on the conditional profits of both technologies, their quantities and shares can be defined as

$$(5) \quad q_i = f_i(p_H, p_{\bar{H}}, Q) \qquad i = H \text{ and } \bar{H}, \text{ and}$$
$$k_i = f_i \Big/ \sum_i f_i, \qquad i = H \text{ and } \bar{H},$$

where $k_H = q_H/Q$ and $k_{\bar{H}} = q_{\bar{H}}/Q$ are acreage shares of the respective technologies, which sum to one and are interpreted as probabilities of adopting the respective technologies. If we further assume

$$(6) \quad f_i = \exp[g_i(p_H, p_{\bar{H}}, Q)], \qquad i = H \text{ and } \bar{H},$$

then k_i is defined as a universal logit function (Amemiya). A convenient expression is then derived by taking the natural logarithm of the probability ratio, or odds ratio:

$$(7) \quad \ln(k_H/k_{\bar{H}}) = \ln(q_H/q_{\bar{H}}) = z_H = g_H - g_{\bar{H}}.$$

Equation (7) can be estimated using standard econometric methods if it is stochastic and linear in its arguments, and an estimate of the probability of adopting herbicide-resistant cotton seed can be obtained.

Conditional elasticities for q_H and $q_{\bar{H}}$ with respect to an explanatory variable can be calculated as in Roberts and Garrod. These elasticities, for variables other than Q, approach zero as k_i ($i = H$ or $\bar{H}$) approaches unity, suggesting that as the choice becomes limited to one alternative, that alternative cannot change in the short run because $q_i = Q$ is fixed. Also, the weighted sum of these two elasticities equals zero, where the weights are the acreage shares in each seed technology; thus, in the short run, cotton acreage in herbicide-tolerant seed cannot increase (or decrease) without decreasing (or increasing) acreage in conventional seed. For Q, the weighted sum of the elasticities is unity. If acreage in conservation-tillage practices is an argument of z_H, the influence of conservation-tillage adoption on the adoption of herbicide-tolerant seed, and its complement can be evaluated through their respective elasticities.

A similar model can be hypothesized for the choice between the use of conservation-tillage (C) and conventional tillage ($\bar{C}$) practices:

$$(8) \quad \ln(k_C/k_{\bar{C}}) = \ln(q_C/q_{\bar{C}}) = z_C = g_C - g_{\bar{C}},$$

where $k_j = q_j/Q$ ($j = C$ and $\bar{C}$); q_j is acreage in technology j ($j = C$ and $\bar{C}$); and $Q = q_c + q_{\bar{C}}$. We hypothesize that adoption of conservation-tillage practices is not independent of herbicide-resistant cotton seed adoption, suggesting that acreage in herbicide-resistant seed is an argument of z_C. If indeed acreage in conservation-tillage practices is an argument in Equation (7) and acreage in herbicide-resistant seed is an argument in Equation (8), these two equations form a system of simultaneous equations that must be estimated with appropriate econometric methods that account for simultaneity.

For empirical estimation, Equations (7) and (8) were specified as

$$(9) \quad \ln\left(\frac{HAC}{100 - HAC}\right) = \beta_0 + \beta_1 CAC + \beta_2 RUPR/COPR + \beta_3 RSPR/CSPR + \beta_4 D + \beta_5 CTAC + e_H,$$

and

$$(10) \quad \ln\left(\frac{CAC}{100 - CAC}\right) = \gamma_0 + \gamma_1 HAC + \gamma_2 RUPR/FUPR + \gamma_3 RAIN + \gamma_4 DRAIN + \gamma_5 NRAIN + \gamma_6 CTAC + e_C,$$

where variable definitions and means are given in Table 1 the βs and γs are parameters to be estimated; and e_H and e_C are random errors.

Table 1. Logit Model Variables, Definitions, and Means

Variable	Definition	Mean[a]
$\ln\left(\frac{HAC}{100 - HAC}\right)$	Natural logarithm of the ratio of the percentage of Tennessee cotton acres in herbicide-resistant seed (Roundup Ready, BXN, and Liberty Link, including stacked genes) to the percentage in conventional seed	1.80 (1.11)
$\ln\left(\frac{CAC}{100 - CAC}\right)$	Natural logarithm of the ratio of the percentage of Tennessee cotton acres in conservation tillage (no-till, ridge-till, strip-till, and mulch-till) to the percentage in conventional tillage	0.61 (0.20)
HAC	Percentage of Tennessee cotton acres in herbicide-resistant seed	69.31 (42.65)
CAC	Percentage of Tennessee cotton acres in conservation tillage	61.31 (52.58)
RUPR	Roundup price ($/pint)	5.83 (6.08)
COPR	Cotoran price ($/pint)	4.57 (4.93)
RUPR/COPR	Ratio of *RUPR* to *COPR*	1.28 (1.28)
RSPR	Roundup-Ready cotton seed price ($/lb)	1.88 (1.16)
CSPR	Conventional cotton seed price ($/lb)	1.01 (0.90)
RSPR/CSPR	Ratio of *RSPR* to *CSPR*	1.87 (1.15)
D	Dummy equals 1 for 1999 through 2004; 0 otherwise	0.75 (0.46)
CTAC	Total Tennessee cotton acres (100,000s)	5.52 (5.77)
FUPR	U.S. index of prices paid by farmers for fuel, 2002 = 1.00	1.07 (0.98)
RUPR/FUPR	Ratio of *RUPR* to *FUPR* lagged one period	6.35 (6.88)
RAIN	County average cumulative rainfall for April and May for the five highest cotton-producing counties in Tennessee (inches)	10.62 (9.96)
DRAIN	Dummy equals *RAIN* if *RAIN* is greater than one-half standard deviation above its mean (>11.16 inches); 0 otherwise	5.00 (3.08)
NRAIN	Dummy equals 1 if November rainfall in the previous year was greater than one-half standard deviation from its mean (>4.97 inches); 0 otherwise	0.38 (0.5)

[a] Means of annual data for 1997 through 2004, with means for 1992 through 2004 in parentheses.

Equations (9) and (10) were estimated with three-stage least squares using Tennessee annual time-series data for the 1992–2004 period. The Roundup price (*RUPR*) was taken from Economic Research Service (1997) and National Agricultural Statistics Service (2005, 2003, 2000, 1996a, 1996b). Cotoran (*COPR*), Roundup-Ready seed (*RSPR*), and conventional seed (*CSPR*) prices were taken from annual Tennessee field crop and cotton budgets (Johnson 1992–1993; Gerloff 1994–1999; Gerloff 2000–2004). The U.S. index of prices paid by farmers for fuel (*FUPR*) was taken from the Council of Economic Advisors. Data for the rainfall variables (*RAIN, DRAIN,* and *FRAIN*) were received from the National Climatic Data Center. The percentages of Tennessee cotton acreage in conservation-tillage (*CAC*) and conventional tillage (100-*CAC*), and total cotton acreage (*CTAC*) were found in Tennessee Department of Agriculture (1996–2003, 2004). Data used in the conditional probability analysis for the share of Tennessee cotton acreage in conservation-tillage practices provided by Doane Marketing Research, Inc. were not used for *CAC* because those tillage data only covered the 1998–2004 period. Tillage data from Tennessee Department of Agriculture allowed estimation of Equations (9) and (10) with time-series data for 1992 through 2004.

The *HAC* data for 1995 through 1997 were

not available from Doane. *HAC* was zero for 1992 through 1994 because herbicide-resistant cotton seed was not available to farmers in those years, and it was assumed zero for 1995 and 1996 because herbicide-resistant cotton seed adoption in Tennessee was sufficiently small (Alesii and Bradley, personal communication) for *HAC* to be considered zero without appreciably affecting the analysis. Data for *HAC* for 1998 through 2004 were received from Doane Marketing Research, Inc. Monsanto (Alesii and Bradley, personal communication) provided their best estimate for *HAC* in 1997 of about half the Doane 1998 level, which was used in the logit analysis. Acreage elasticities were calculated at the means of the data for 1997–2004 (instead of 1992–2004) to provide a more consistent view of acreage responsiveness during the period when herbicide-resistant seed was available and being adopted by farmers.

The price variables in Equations (9) and (10) were used as proxies for prices of inputs hypothesized to make the most difference in relative profitability for the respective technology choices. Other prices were not considered because of general colinearity among prices and to preserve degrees of freedom. Price ratios were used for similar reasons.

Prices of cotton lint produced with herbicide-resistant and conventional seed and with conservation and conventional tillage practices were not included in Equations (9) and (10) for two reasons. First, prices for cotton lint produced with the different technologies are not different unless these technologies produce lint of different qualities. Concern has been expressed about a potential loss in lint quality from herbicide-resistant seed (e.g., Bourland and Johnson; Coley; Ethridge and Hequet; Kerby et al.; Lewis; Verhalen, Greenhagen, and Thacker), although York et al. found no difference in lint quality compared with conventional cultivars in official North Carolina cultivar trails. Daniel et al. and Bauer and Busscher found no differences in lint quality among tillage systems. Even if differences in price discounts for lint quality existed, they would likely have little effect on the results because their magnitudes would be small relative to the magnitudes of the prices of lint produced with these technologies. Second, separate time-series data do not exist for prices of lint produced with the technologies evaluated in this analysis.

The expected lint price might still be included in Equations (9) and (10) if changes in the lint price changed the relative profitabilities for each technology choice because of differences in yields and/or production costs. Nevertheless, the expected lint price was excluded for five reasons. First, research suggests that lint yields are about the same for conservation and conventional tillage practices (e.g., Bradley, 1991, 1997; Bronson et al.; Buman et al.; Daniel et al.; Hudson; Keeling, Segarra, and Abernathy; York et al.). Second, differences in budgeted costs between no-tillage and conventional-tillage cotton in Tennessee were from 4% to 6% of total cost regardless of seed technology (Gerloff 2003), suggesting little potential for changes in relative profitabilities as the lint price changes. Third, although some evidence suggests lower lint yields from herbicide-resistant seed (Verhalen, Greenhagen, and Thacker), modeling by Fernandez-Cornejo and McBride (2000) indicated increased lint yields with adoption of herbicide-resistant seed, and Marra, Pardey, and Alston reported research that indicated herbicide-resistant lint yields between 120 lb/acre higher and 164 lb/acre lower than conventional seed yields. Other researchers who conducted field trials found similar yields between the two seed technologies (e.g., Goldman et al.; Keeling et al.; Vencill; York et al.). Fourth, differences in budgeted costs between Roundup Ready and conventional seed cotton were only about 1% of total cost regardless of tillage practice (Gerloff 2003), leaving little room for changes in relative profitabilities as the lint price changes. Fifth, even if the expected lint price affected the acreage allocation decisions in Equations (9) and (10), much of its influence would be transmitted to the decisions through *CTAC*. The expected lint price (among other things) determines *CTAC*, which in turn influences acreage-allocation decisions for the technology choices portrayed in Equations (9) and (10). Thus, the expected

lint price (e.g., lagged price) and *CTAC* would capture similar effects and be highly correlated, producing extreme multicollinearity.

Economic theory and other attributes of the variables in Equations (9) and (10) allowed formation of *a priori* hypotheses about the signs of the parameters. The motivating hypothesis for this research was that adoption of conservation-tillage practices positively influences adoption of herbicide-resistant cotton seed and that adoption of herbicide-resistant seed positively influences adoption of conservation-tillage practices; thus, β_1 and γ_1 were both expected to be positive, indicating that a change in the probability of adopting conservation-tillage cotton (*CAC*) positively influences the probability of adopting herbicide-resistant cotton seed and that a change in the probability of adopting herbicide-resistant cotton seed (*HAC*) positively influences the probability of adopting conservation-tillage practices.

Herbicide-resistant and conventional seed cotton use two distinct herbicide systems. As the cost of one system changes relative to the other, the relative profitability of herbicide-resistant and conventional seed cotton changes and the probability of a profit-maximizing farmer choosing one technology over the other changes. Roundup (*RUPR*) and Cotoran (*COPR*) prices were included in Equation (9) as proxies for the prices of herbicides used to produce herbicide-resistant and conventional seed cotton, respectively. The price of Roundup was chosen because herbicide-resistant cotton is produced almost entirely with Roundup-Ready seed and Roundup cannot be used over top of conventional seed cotton. The price of Cotoran was used because non-Roundup herbicides (e.g., Cotoran and others) are a small part of the cost of producing herbicide-resistant cotton, and Cotoran was a herbicide consistently recommended for conventional seed cotton in the University of Tennessee cotton budgets (Johnson 1992–1993; Gerloff 1994–1999; Gerloff 2000–2004). With Roundup being an input in the production of herbicide-resistant cotton, a change in *RUPR* was expected to negatively influence the probability of adopting herbicide-resistant cotton seed and positively influence the use of conventional cotton seed. Conversely, a change in *COPR* was expected to negatively influence the use of conventional cotton seed and positively influence the probability of adopting herbicide-resistant cotton seed; thus, β_2 was expected to be negative. Similarly, Roundup-Ready cotton seed and conventional cotton seed are inputs in the production of herbicide-resistant cotton and conventional seed cotton, respectively; therefore, β_3 was expected to be negative.

Although herbicide-resistant BXN (Buctril-resistant) cotton seed was first introduced in 1995 (Ward et al. 1995) and Roundup-Ready cotton seed became commercially available in 1996 (Johnson 1996), insufficient supply was available to meet farmer demand until 1999, when most farmers were able to purchase herbicide-resistant cotton seed if they wanted it. The binary variable *D* was included in Equation (9) to account for differences in years when sufficient herbicide-resistant seed was available to meet demand compared with years when herbicide-resistant seed was not available or not available in quantities sufficient to meet demand. Thus, β_4 was expected to be positive.

The sign of γ_2 was expected to be negative because herbicides are a more important input in the production of conservation-tillage cotton and fuel is a more important input in the production of conventional-tillage cotton. Roundup is a commonly used burn-down herbicide in conservation-tillage systems; hence its price was used as a proxy for prices of herbicides used in conservation-tillage systems. A decrease in the price of Roundup (*RUPR*) relative to the price of fuel (*FUPR*) would decrease the cost of producing conservation-tillage cotton relative to the cost of producing conventional-tillage cotton, encouraging farmers to move away from conventional-tillage towards conservation-tillage cotton production.

Conservation-tillage practices reduce the risk of late planting because fewer machinery operations are required and crops can generally be planted when conditions are too wet for conventional-tillage operations (Bates and Denton; Harper; Phillips and Hendrix). Heavy

Table 2. Adoption of Herbicide-Resistant and Conservation-Tillage Cotton for 1998–2004

Proportion of Tennessee Cotton Acreage	1998	1999	2000	2001	2002	2003	2004
Herbicide-resistant, $P(H)$	0.091	0.677	0.845	0.934	0.959	0.998	0.995
Conservation-tillage, $P(C)$	0.364	0.549	0.670	0.777	0.709	0.735	0.782
Herbicide-resistant and conservation-tillage, $P(HC)$	0.061	0.410	0.625	0.732	0.696	0.733	0.781

Source: Doane Marketing Research, Inc.

rainfall during April and May when farmers are engaged in tillage and planting operations makes timely tillage and planting more difficult, increasing the risk of late planting. Heavy spring rainfall was hypothesized to encourage cotton farmers to rent no-till planting equipment, custom hire no-till planting operations, or retrofit their conventional planters for no-till planting (Bradley 2001). Conversely, light spring rainfall might encourage farmers to engage in what some call "recreational tillage" because many farmers feel they should be out working in the field when the weather is good (e.g., Alesii and Bradley, personal communication; Delta Farm Press; Fletcher). The latter occurs because farmers who are affected by heavy spring rainfall are at the margin of conservation-tillage adoption and seldom convert completely by selling their tillage equipment (Dumler). These marginal adopters can bring their tillage equipment back online when the weather is good if they have doubts about the relative profitabilities of the two tillage practices. Therefore, γ_3 was expected to be positive. A positive γ_3 implies that increases in rainfall encourage adoption of conservation-tillage practices by the same amount as decreases in rainfall encourage abandonment of conservation-tillage practices. *DRAIN* was included in Equation (10) to test the hypothesis that April and May rainfall of more than one-half standard deviation above its mean has a different effect on adoption of conservation-tillage practices than rainfall of lesser amounts; thus, γ_4 was expected to be positive.

Heavy rainfall in the previous year (*NRAIN*) may have a different effect on tillage decisions than heavy spring rainfall. It may cause farmers to rut their fields during harvest, requiring spring tillage; thus, the sign of γ_5 would be negative. Alternatively, heavy rainfall in the fall may cause farmers to look toward future spring tillage operations and begin planning for conversion to conservation tillage to avoid a perceived risk of late planting. If farmers apply past heavy rainfall to their tillage decisions in this way, γ_5 would be positive; thus, the sign of γ_5 was ambiguous.

Theoretically, cotton is produced on the "best" cotton land in terms of potential profit compared with other crops. Consequently, changes in cotton acreage would typically occur on marginal cotton land that may be more erodible than land that is already in cotton production. We hypothesized that farmers are more likely to use conservation-tillage practices on this marginal land than on the less-erodible land already in cotton production; thus, γ_6 was expected to be positive. Farmers who increase cotton acreage or who produce cotton for the first time may be less risk averse than those who do not, and they may be more willing to adopt new technologies. If this hypothesis were correct, β_5 would be positive, and the positive expectation for γ_6 would be reinforced.

Results

Bayes' Theorem

Shares of Tennessee cotton acreage produced with each technology and with both technologies for 1998 through 2004 are presented in Table 2 and the conditional probabilities in Equations (1) through (4) are presented in Table 3. In all years except in 2003, the conditional probability of using herbicide-resistant seed given conservation-tillage practices, $P(H|C)$, is greater than the conditional prob-

Table 3. Conditional Probabilities Showing the Relationships Between Adoption of Herbicide-Resistant Cotton Seed and Conservation-Tillage Cotton Production Practices, 1998–2004

Conditional Probability	1998	1999	2000	2001	2002	2003	2004
$P(H\|C)$	0.169	0.747	0.932	0.968	0.981	0.997	0.999
$P(H\|\bar{C})$	0.047	0.593	0.668	0.817	0.905	1.000	0.981
$P(C\|H)$	0.674	0.605	0.740	0.805	0.726	0.735	0.785
$P(C\|\bar{H})$	0.333	0.431	0.294	0.377	0.331	1.000	0.143

[a] $P(H|C)$ and $P(H|\bar{C})$ are conditional probabilities of a Tennessee cotton acre being produced with herbicide-resistant seed (H) given that it is produced with conservation-tillage practices (C) or conventional-tillage practices ($\bar{C}$), respectively. $P(C/H)$ and $P(C|\bar{H})$ are conditional probabilities of a Tennessee cotton acre being produced with C given that it is produced with H or conventional cotton seed ($\bar{H}$), respectively.

ability of using herbicide-resistant seed given conventional tillage practices, $P(H|\bar{C})$, which indicates that cotton farmers who had adopted conservation-tillage practices had a higher probability of adopting herbicide-resistant cotton seed than those farmers who had not adopted conservation-tillage practices. This finding suggests that diffusion of herbicide-resistant seed technology was faster among farmers who used conservation-tillage practices than among those who did not. Also, the gap between $P(H|C)$ and $P(H|\bar{C})$ narrows over time, and in 2003 and 2004 these conditional probabilities are almost equal to each other and equal to the marginal probability of adopting herbicide-resistant seed ($P(H)$ in Table 2), suggesting that differences in tillage practices had less influence on the probability of adopting herbicide-resistant seed in later years because almost all Tennessee cotton acreage was in herbicide-resistant seed in 2003 and 2004 regardless of tillage method.

Results also suggest that adoption of herbicide-resistant cotton seed influenced the probability of adopting conservation-tillage practices as indicated by $P(C|H)$ being greater than $P(C|\bar{H})$ every year except 2003 (Table 3). In this case, however, the gap between the two conditional probabilities does not narrow over time, indicating that adoption of herbicide-resistant seed continued to have an influence through time on the probability of adopting conservation-tillage practices. The conditional probability of 1 in 2003 resulted from only 1,088 Tennessee cotton acres being produced with conventional cotton seed in that year, all of which were produced with conservation-tillage practices.

The Bayes' results suggest a simultaneous relationship between adoption of herbicide-resistant cotton seed and adoption of conservation-tillage practices. These results bode well for the simultaneity hypothesis in the logit analysis.

Logit Analysis

Results from the simultaneous logit model estimated with three-stage least squares are presented in Table 4. All coefficients but one have their hypothesized signs and the high system weighted-average R^2 (0.95) suggests a good fit to the data. Multicollinearity diagnostics (Belsley, Kuh, and Welsch) indicated collinearity between the intercept and *CTAC* in both equations. Thus, multicollinearity may have seriously degraded the standard errors of the coefficients for *CTAC*, rendering the results from hypothesis testing inconclusive for those coefficients (Belsley, Kuh, and Welsch).

Results from the estimation of Equation (9) in Table 4 suggest that the probability of adopting conservation-tillage practices (*CAC*) significantly influenced the probability of adopting herbicide-resistant cotton seed and results from the estimation of Equation (10) indicate that the probability of adopting herbicide-resistant seed (*HAC*) significantly influenced the probability of adopting conservation-tillage practices for Tennessee cotton production. As suggested by the conditional probability results in Table 3 and the 1997–

Table 4. Three-Stage Least Squares Regression and Elasticities for Cotton Acreage Logit Model

Herbicide-Resistant Seed, Equation (9)			Conservation-Tillage Practices, Equation (10)		
Variable[a]	Parameter Estimate	Elasticity[b]	Variable[a]	Parameter Estimate	Elasticity[b]
INTERCEPT	0.586 (5.545)[c]		*INTERCEPT*	−2.071 (1.344)	
CAC	0.092*** (0.027)	1.74[d] [−3.92]	*HAC*	0.009*** (0.002)	0.24[e] [−0.38]
RSPR/CSPR	−1.258 (1.231)	−0.50 [1.12]	*RUPR/FUPR*	−0.148* (0.062)	−0.36 [0.57]
	−1.353* (0.650)	−0.78 [1.75]	*RAIN*	0.111** (0.042)	0.46 [−0.72]
D	2.601* (1.392)	0.60 [−1.35]	*DRAIN*	0.023 (0.026)	0.55[f] [−0.87]
			NRAIN	0.558* (0.238)	0.11 (−0.17)
CTAC	−0.410 (0.767)	0.31 [2.57]	*CTAC*	0.232 (0.161)	1.56 [0.11]
System-weighted R^2		0.95	System degrees of freedom		13

[a] Variables are defined in Table 1.

[b] Elasticities are calculated at the 1997–2004 means of the variables.

[c] Numbers in parentheses are asymptotic standard errors.

[d] Percentage change in cotton acres in herbicide-resistant seed for a 1% change in the variable in the row. Elasticities in brackets are for conventional seed.

[e] Percentage change in the number of cotton acres in conservation-tillage practices for a 1% change in the variable in the row. Elasticities in brackets are for conventional-tillage practices.

[f] Elasticities calculated using the sum of the coefficients for RAIN and DRAIN at the mean of RAIN.

*, **, *** Significantly different from zero at the 10%, 5%, and 1% levels, respectively.

2004 mean elasticities in Table 4, these influences are not symmetric. While both elasticities are positive, the number of cotton acres in herbicide-resistant seed increases (decreases) by 1.74% for a 1% increase (decrease) in the probability of adopting conservation-tillage practices (*CAC*), while the number of cotton acres in conservation-tillage practices increases (decreases) by only 0.24% for a 1% increase (decrease) in the probability of adopting herbicide-resistant seed (*HAC*).

Results for Equation 9 (Table 4) also indicate that the short-run supply of Tennessee cotton acreage in herbicide-resistant seed increases (decreases) by 0.78% when the Roundup Ready cotton seed price decreases (increases) by 1% relative to the conventional cotton seed price (*RSPR/CSPR*) and that the probability of adopting herbicide-resistant seed was higher during the 1999–2004 period than in earlier years when it was not available, or before sufficient supply of herbicide-resistant seed was produced to meet demand, as evidenced by the positive coefficient for D.

Findings from Equation (10) suggest that the short-run supply of Tennessee cotton acreage in conservation-tillage increases (decreases) by 0.36% when the price of Roundup decreases (increases) by 1% relative to the price of fuel (*RUPR/FUPR*) (Table 4). In addition, the finding that the coefficient for *RAIN* is statistically significant, while the coefficient for *DRAIN* is not, suggests that symmetry exists in cotton farmers' response to increases or decreases in spring rainfall. The elasticity for *RAIN* indicates that conservation-tillage cotton acreage increases by 0.46% when spring rainfall increases by 1% and it decreases by the same amount when rainfall decreases by 1%, other things remaining constant. The positive coefficient for *NRAIN* suggests that heavy rainfall in the fall of the previous year increases the probability that cotton farmers will adopt conservation-tillage practices in the spring.

Conclusions

Results suggest that the introduction of herbicide-resistant cotton seed in Tennessee increased the probability that farmers would adopt conservation-tillage practices. Along with the direct benefits of increased profit potential and the substitution of nonresidual herbicides for residual herbicides, the introduction of herbicide-resistant cotton seed indirectly contributed to increased conservation of Tennessee soils. This indirect environmental benefit of reduced soil erosion should not be ignored when considering the costs and benefits of herbicide-resistant cotton production. Also, farmers who had previously adopted conservation-tillage practices were more likely to adopt herbicide-resistant cotton seed, indirectly reducing their use of residual herbicides and increasing their profit potential as they reduced erosion. Thus, the synergistic relationship between adoption of herbicide-resistant cotton seed and adoption of conservation-tillage practices for cotton production likely contributed to reduced soil erosion, reduced residual herbicide use, and increased profit during a period of low cotton prices.

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