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**Adoption of No-Tillage Practices, Other Conservation-Tillage Practices and Herbicide-Resistant Cotton Seed, and Their Synergistic Environmental Impacts**

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# **Adoption of No-Tillage Practices, Other Conservation-Tillage Practices and Herbicide-Resistant Cotton Seed, and Their Synergistic Environmental Impacts**

## **Introduction**

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”. Fernandez-Cornejo and McBride used 1997 ARMS data and simultaneous estimation of two binomial probit models to evaluate the potential synergistic relationship between herbicide-resistant soybean seed and no-tillage practices. Contrary to Monsanto’s claim, they found no evidence that soybean farmers who 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 adopt 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 between adoption of these technologies over time. In our research, annual time-series data and simultaneous estimation of a trinomial logit model for no-tillage, other conservation-tillage and conventional-tillage cotton production, and a binomial logit model for herbicide-resistant and conventional-seed cotton production were used to examine the relationship between adoption of herbicide-resistant seed and adoption of conservation-tillage (no-tillage and other 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 objectives of this research were: 1) to evaluate the relationships among adoption of herbicide-resistant cotton seed and no-tillage and other conservation-tillage cotton production practices over time, 2) to quantify the effects of economic phenomena on the adoption of herbicide-resistant seed and no-tillage and other conservation-tillage practices for cotton production in Tennessee, 3) to evaluate the synergistic effects of these production technologies on acreages in herbicide-resistant seed and no-tillage and other conservation-tillage practices, and their potential environmental impacts.

## 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.

Following Garrod and Roberts, assume cotton production can be accomplished during a particular year using herbicide-resistant (H) or conventional-seed ( $\bar{H}$ ) 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:

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

$$k_i = f_i / \sum_i f_i, i = H \text{ and } \bar{H},$$

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:

$$(6) \quad f_i = e^{g_i(p_H, p_{\bar{H}}, Q)}, i = H \text{ and } \bar{H},$$

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:

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

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-resistant 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-resistant seed and its complement can be evaluated through their respective elasticities.

A similar model is hypothesized for the choice among no-tillage (N), other conservation-tillage (O), and conventional-tillage (C) practices except the model would be trinomial with two equations for logarithms of odds ratios as follows:

$$(8) \quad \text{Ln}(k_N/k_C) = \text{Ln}(q_N/q_C) = z_N = g_N - g_C, \text{ and}$$

$$(9) \quad \text{Ln}(k_O/k_C) = \text{Ln}(q_O/q_C) = z_O = g_O - g_C,$$

where  $k_j = q_j/Q$  ( $j = N, O, \text{ and } C$ );  $q_j$  is acreage in technology  $j$  ( $j = N, O, \text{ and } C$ ); and

$Q = q_N + q_O + q_C$ . Only two equations are necessary because the parameters of  $z_C$  are normalized to zero ( $z_C = g_C - g_C$ ) (Greene). Acreage elasticities are calculated as in Garrod and Roberts.

We hypothesize that adoption of no-tillage and other conservation-tillage practices is not independent of herbicide-resistant cotton seed adoption, suggesting that acreage in herbicide-resistant seed is an argument of  $z_N$  and  $z_O$ . If indeed acreage in conservation-tillage practices is an argument in equation (7) and acreage in herbicide-resistant seed is an argument in equations (8) and (9), these three equations form a system of simultaneous equations that must be estimated with appropriate econometric methods that account for simultaneity.

For empirical estimation, equations (7), (8), and (9) were specified as:

$$(10) \quad \text{Ln}\left(\frac{\text{HAC}}{100 - \text{HAC}}\right) = \beta_{H0} + \beta_{H1}(\text{NAC} + \text{OAC}) + \beta_{H2}\text{RUPR}/\text{COPR} + \beta_{H3}\text{RSPR}/\text{CSPR} + \beta_{H4}\text{D} \\ + \beta_{H5}\text{CTAC} + e_H,$$

$$(11) \quad \text{Ln}\left(\frac{\text{NAC}}{\text{CAC}}\right) = \gamma_{N0} + \gamma_{N1}\text{HAC} + \gamma_{N2}\text{CHPR}/\text{FUPR} + \gamma_{N3}\text{RAIN} + \gamma_{N4}\text{DRAIN} + \gamma_{N5}\text{CTAC} + e_N,$$

and

$$(12) \quad \text{Ln}\left(\frac{\text{OAC}}{\text{CAC}}\right) = \gamma_{00} + \gamma_{01}\text{HAC} + \gamma_{02}\text{CHPR/FUPR} + \gamma_{03}\text{RAIN} + \gamma_{04}\text{DRAIN} + \gamma_{05}\text{CTAC} + e_o,$$

where variable definitions and means are given in table 1; the  $\beta$ s and  $\gamma$ s are parameters to be estimated; and  $e_H$ ,  $e_N$  and  $e_O$  are random errors.

Equations (10), (11), and (12) were estimated with three-stage least squares using Tennessee annual time-series data for the 1992-2004 period. Estimation with three-stage least squares accounts for 1) the simultaneity introduced by having endogenous variables on the right-hand sides of these equations, 2) the correlation between  $e_N$  and  $e_O$  introduced by the trinomial logit specification of equations (11) and (12), and 3) the possible correlation of  $e_N$  and  $e_O$  with  $e_H$ .

Roundup (RUPR), 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. indexes of prices paid by farmers for chemicals (CHPR) and fuel (FUPR) were taken from the Council of Economic Advisors. Data for the rainfall variables (RAIN and DRAIN) were received from the National Climatic Data Center. Total cotton acreage (CTAC) and percentages of Tennessee cotton acreage in no-tillage (NAC), other conservation-tillage (OAC) and conventional-tillage (CAC) practices were found in Tennessee Department of Agriculture (1996-2003, 2004).

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). Data for HAC for 1998 through 2004 were received from Doane Marketing Research, Inc., but 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. Monsanto (Alesii and Bradley, personal communication) provided their best estimate of HAC for 1997 of about half the Doane 1998 level.

Price variables in equations (10) through (12) were used as proxies for prices of inputs hypothesized to make the most difference in relative profitabilities for the respective technology choices. Other prices were not considered because of general collinearity 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 no-tillage, other conservation-tillage, and conventional-tillage practices were not included in equations (10) through (12) for three 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 (eg., 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 trials. Daniel et al. and Bauer and Busscher found no differences in lint quality among tillage systems. Second, 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. Third, separate time-series data do not exist for prices of lint produced with the technologies evaluated in this analysis.

Economic theory and other attributes of the variables in equations (10) through (12) 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 no-tillage and other conservation-tillage practices; thus,  $\beta_{HI}$ ,  $\gamma_{NI}$ , and  $\gamma_{OI}$  were expected to be positive, indicating that a change in the probability of adopting conservation-tillage cotton (NAC+OAC) 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 no-tillage and other conservation-tillage practices.

Roundup (RUPR) and Cotoran (COPR) prices were included in equation (10) 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-the-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,  $\beta_{H2}$  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,  $\beta_{H3}$  was expected to be negative.

Although herbicide-resistant cotton seed was first introduced in the mid-1990s (Johnson, 1996; Ward et al., 1995), 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 (10) 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,  $\beta_{H4}$  was expected to be positive.

The signs of  $\gamma_{N2}$  and  $\gamma_{O2}$  were 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. A decrease in the chemical price (CHPR) relative to the fuel price (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 toward no-tillage and other 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 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 practice no-tillage and other conservation-tillage practices. For example, they might rent no-till planting equipment, custom

hire no-till planting operations, retrofit their conventional planters for no-till planting (Bradley), or engage in other reduced-tillage practices. 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 to no-tillage by selling their tillage equipment (Dumler). These marginal adopters can bring their tillage equipment back on line when the weather is good if they have doubts about the relative profitabilities of tillage practices. Therefore,  $\gamma_{N3}$  and  $\gamma_{O3}$  were expected to be positive. Positive parameters imply 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 equations (11) and (12) 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,  $\gamma_{N4}$  and  $\gamma_{O4}$  were expected to be positive.

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,  $\gamma_{N5}$  and  $\gamma_{O5}$  were 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,  $\beta_{H5}$  would be positive, and the positive expectations for  $\gamma_{N5}$  and  $\gamma_{O5}$  would be reinforced.

Impacts of the synergistic relationship between adoption of herbicide-resistant cotton seed and conservation-tillage practices were evaluated with three scenarios. These scenarios were 1) use historical data for the explanatory variables in equations (10) through (12) to estimate cotton acreage in herbicide-resistant seed and no-tillage and other conservation-tillage practices, 2) estimate cotton acreage in herbicide-resistant seed assuming conservation-tillage practices for 1998 through 2004 in equation (10) were set equal to their 1992-1997 means, and 3) estimate cotton acreage in no-tillage and other conservation-tillage practices assuming herbicide-resistant seed was never available;  $HAC = 0$  in equations (11) and (12). The impact of conservation-tillage adoption on acreage in herbicide-resistant seed was estimated by subtracting scenario 2 from scenario 1, and the impacts of herbicide-resistant seed adoption on acreages in no-tillage and other conservation-tillage practices were estimated by subtracting results for scenario 3 from scenario 1.

Acreage impacts on no-tillage, other conservation-tillage, and conventional-tillage practices were converted to tons of soil that would have been lost on Tennessee cotton lands without the availability of herbicide-resistant cotton seed. This conversion was accomplished in four steps. First, Tennessee no-tillage, other conservation-tillage, and conventional-tillage cotton acres were classified based on information from the 1997 National Resources Inventory (U.S. Department of Agriculture). The acreage in each area segment having land in cotton was classified as no-tillage if the C Factor was less than 0.1, other conservation-tillage if the C Factor was between 0.1 and 0.2, and conventional-tillage if the C Factor was greater than 0.2. Second, the amount of soil erosion for a particular tillage class was divided by acreage in that tillage class

to derive an erosion estimate for each tillage practice (tons/acre). Third, erosion estimates were multiplied by their respective acreage impacts estimated from the logit models to obtain soil erosion impacts for each tillage practice. Fourth, soil erosion impacts were summed across tillage practices to estimate total tons of soil that would have been lost without the availability of herbicide-resistant cotton seed in Tennessee.

## **Results**

Results from the simultaneous binomial and trinomial logit models estimated with three-stage least squares are presented in tables 2 and 3. All coefficients but three 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 all 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 (10) in table 2 suggest that the probability of adopting conservation-tillage practices (NAC + OAC) significantly influenced the probability of adopting herbicide-resistant cotton seed and results from the estimation of equations (11) and (12) indicate that the probability of adopting herbicide-resistant seed (HAC) significantly influenced the probabilities of adopting no-tillage and other conservation-tillage practices for Tennessee cotton production. As suggested by the elasticities in tables 2 and 3, these influences are not symmetric. The number of cotton acres in herbicide-resistant seed increases (decreases) by 3.98% for a 1% increase (decrease) in the probability of adopting conservation-tillage practices (NAC + OAC), while the numbers of cotton acres in no-tillage and other conservation-tillage practices increase (decrease) by only 0.34% and 0.10%, respectively, for a 1% increase

(decrease) in the probability of adopting herbicide-resistant seed (HAC). These results indicate that synergy between seed and tillage technologies had a large influence on the rapid adoption of herbicide-resistant cotton seed in Tennessee, while this synergy played a lesser role in increasing the adoption of no-tillage practices, and had a smaller influence on increasing the adoption of other conservation-tillage practices.

Results for equation (10) (table 2) also indicate that the short-run supply of Tennessee cotton acreage in herbicide-resistant seed increases (decreases) by 0.74% when the Roundup Ready cotton seed price decreases (increases) by 1% relative to the conventional cotton seed price (RSPR/CSPR).

Findings from equation (11) suggest that the short-run supplies of Tennessee cotton acreage in no-tillage and other conservation-tillage practices increase (decrease) by 0.09% and 2.29%, respectively, when the chemical price decreases (increases) by 1% relative to the fuel price (CHPR/FUPR) (table 3). Thus, the ratio of chemical to fuel prices has more influence on other conservation-tillage practices than on no-tillage practices. This finding is not surprising since many farmers dabble with other conservation-tillage practices at the margin before selling their tillage equipment and converting to no-tillage practices (Dumler). This strategy preserves the option of converting back to conventional-tillage if prices change or profit expectations are not met for other reasons.

The finding that the coefficient for RAIN is statistically significant in equations (11) and (12), while the coefficient for DRAIN is not, suggests that symmetry exists in cotton farmers' responses to increases or decreases in spring rainfall. The elasticities for RAIN indicate that no-tillage and other conservation-tillage cotton acres increase by 0.60% and 1.20% when spring rainfall increases by 1% and they decrease by the same amounts when rainfall decreases by 1%,

other things remaining constant. That the acreage elasticity for other conservation-tillage practices is twice the elasticity for no-tillage practices can be explained by the same reasoning as presented in the previous paragraph; farmers who are at the margin of adopting conservation-tillage practices are more likely to dabble with other conservation-tillage practices than no-tillage practices before converting fully to no-tillage practices.

The estimated impacts of the synergistic relationships among seed and tillage technologies on Tennessee cotton acreage are presented in figure 1. Synergy with conservation-tillage practices was estimated to increase herbicide-resistant cotton production by 445 thousand acres in 2004, an increase from 138 thousand acres (23% of total cotton acres) without synergy to 583 thousand acres (99% of total cotton acres) with synergy. Thus, adoption of conservation-tillage practices encouraged Tennessee cotton farmers to convert a large portion of their cotton acreage from conventional-seed technology, which relies largely on residual herbicides, to herbicide-resistant seed technology, which relies mostly on over-the-top applications of non-residual herbicides.

Synergy with herbicide-resistant seed adoption was estimated to increase no-tillage cotton production by 147 thousand acres in 2004, up from 159 thousand acres (27% of total cotton acres) without synergy to 306 thousand acres (52% of total cotton acres) with synergy. In the same year, other conservation-tillage acreage increased by 12 thousand acres because of the availability of herbicide-resistant cotton seed, up from 150 thousand acres (25% of total cotton acres) without synergy to 163 thousand acres (28% of total cotton acres) with synergy. Differences in no-tillage and other conservation-tillage acreage responses to the availability of herbicide-resistant seed come from the larger coefficient for HAC (0.015 versus 0.009) in table 3 and its acreage elasticity (0.34 versus 0.10) for no-tillage relative to other conservation-tillage



practices. Taken together, the proportion of acreage in all conservation-tillage practices was estimated to increase from 52% without herbicide-resistant seed to 80% with herbicide-resistant seed in 2004. This increased acreage in conservation-tillage practices was estimated to have reduced soil erosion by 1.6 million tons in 2004 (figure 2). The accumulated reduction in soil erosion since the introduction of herbicide-resistant cotton seed was estimated at 9.2 million tons.

### **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 non-residual 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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**Table 1:** Logit Model Variables, Definitions, and Means

Variable	Definition	Mean <sup>a</sup>
$\text{Ln}\left(\frac{\text{HAC}}{100 - \text{HAC}}\right)$	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	1.11
$\text{Ln}\left(\frac{\text{NAC}}{\text{CAC}}\right)$	Natural logarithm of the ratio of the percentage of Tennessee cotton acres in no-tillage practices to the percentage in conventional-tillage practices	-0.21
$\text{Ln}\left(\frac{\text{OAC}}{\text{CAC}}\right)$	Natural logarithm of the ratio of the percentage of Tennessee cotton acres in other conservation-tillage (ridge-till, strip-till, and mulch-till) to the percentage in conventional-tillage practices	-0.97
HAC	Percentage of Tennessee cotton acres in herbicide-resistant seed	42.65
NAC	Percentage of Tennessee cotton acres in no-tillage practices	35.63
OAC	Percentage of Tennessee cotton acres in other conservation-tillage practices	16.95
CAC	Percentage of Tennessee cotton acres in conventional-tillage practices	47.42
RUPR	Roundup price (\$/pint)	5.65
COPR	Cotoran price (\$/pint)	4.93
RUPR/COPR	Ratio of RUPR to COPR	1.17
RSPR	Roundup-Ready cotton seed price (\$/lb)	1.16
CSPR	Conventional cotton seed price (\$/lb)	0.90
RSPR/ CSPR	Ratio of RSPR to CSPR	1.15
D	Dummy equals 1 for 1999 through 2004; 0 otherwise	0.46
CTAC	Total Tennessee cotton acres (100,000s)	5.77
CHPR	U.S index of prices paid by farmers for chemicals, 2002=1.00	0.99
FUPR	U.S index of prices paid by farmers for fuel, 2002=1.00	0.98
CHPR/FUPR	Ratio of CHPR to FUPR lagged one period	1.06
RAIN	County average cumulative rainfall for April and May for the five highest cotton producing counties in Tennessee (inches)	9.96
DRAIN	Dummy equals RAIN if RAIN is greater than one-half standard deviation above its mean (>11.16 inches); 0 otherwise	3.08

<sup>a</sup> Means of annual data for 1992 through 2004.



**Table 2.** Three-Stage Least Squares Regression and Cotton Acreage Elasticities for the Binomial Logit Model for Seed Technology

Variable <sup>a</sup>	Parameter Estimate Equation (10)	Acreage Elasticity	
		Herbicide-Resistant Seed <sup>b</sup>	Conventional Seed <sup>b</sup>
INTERCEPT	-3.828 (4.463) <sup>c</sup>		
NAC + OAC	0.132*** (0.040)	3.98	-2.96
RUPR/COPR	-0.690 (1.494)	-0.46	0.35
RSPR/CSPR	-1.124** (0.424)	-0.74	0.55
D	1.170 (1.808)	0.31	-0.23
CTAC	-0.075 (0.660)	0.75	1.18
System Weighted R <sup>2</sup>	0.95	System Degrees of Freedom	21

<sup>a</sup> Variables are defined in table 1.

<sup>b</sup> Elasticities are calculated at the 1992-2004 means of the variables.

<sup>c</sup> Numbers in parentheses below parameter estimates are asymptotic standard errors.

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

**Table 3.** Three-Stage Least Squares Regression and Cotton Acreage Elasticities for the Trinomial Logit Model for Tillage Practices

Variable <sup>a</sup>	Parameter Estimates		Acreage Elasticities		
	Equation (11)	Equation (12)	No-Tillage <sup>b</sup>	Other Conservation-Tillage <sup>b</sup>	Conventional-Tillage <sup>b</sup>
INTERCEPT	-1.380 (1.354) <sup>c</sup>	-0.516 (1.537)			
HAC	0.015*** (0.003)	0.009*** (0.002)	0.34	0.10	-0.29
CHPR/FUPR	-0.912 (0.704)	-2.787*** (0.675)	-0.09	-2.29	0.88
RAIN	0.148** (0.052)	0.208** (0.069)	0.60	1.20	-0.88
DRAIN	-0.016 (0.020)	-0.040 (0.030)	0.56 <sup>d</sup>	0.93 <sup>d</sup>	-0.75 <sup>d</sup>
CTAC	0.013 (0.185)	0.065 (0.188)	1.43	1.04	0.67

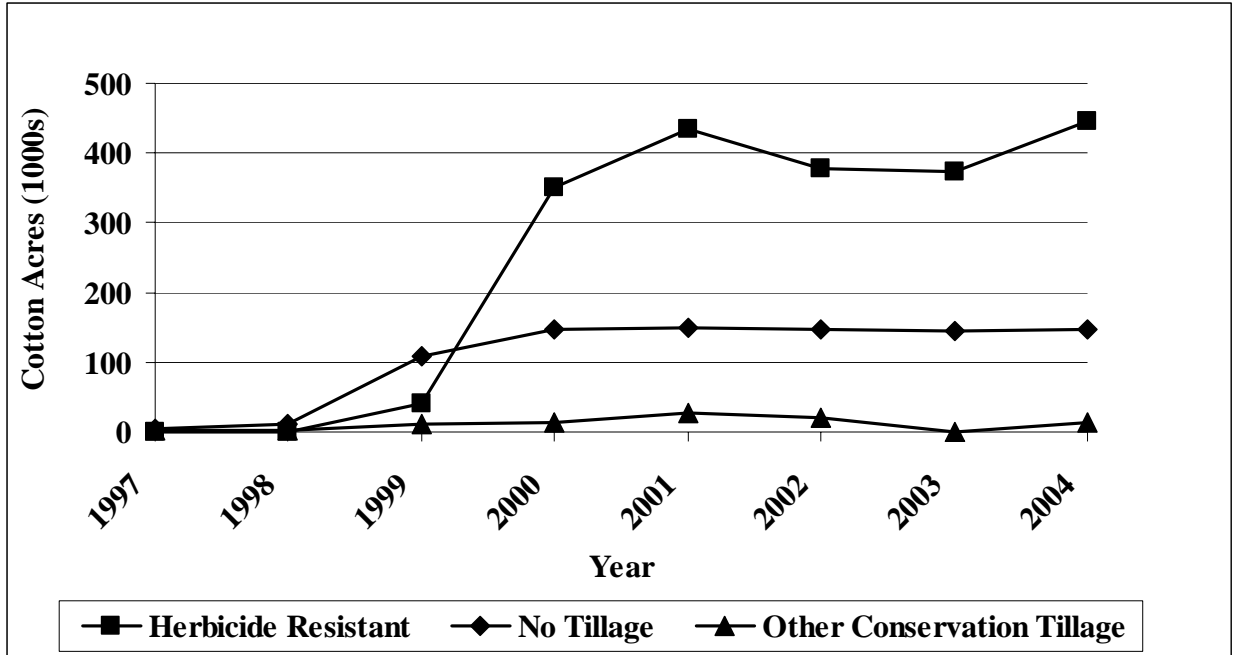
<sup>a</sup> Variables are defined in table 1.

<sup>b</sup> Elasticities are calculated at the 1992-2004 means of the variables.

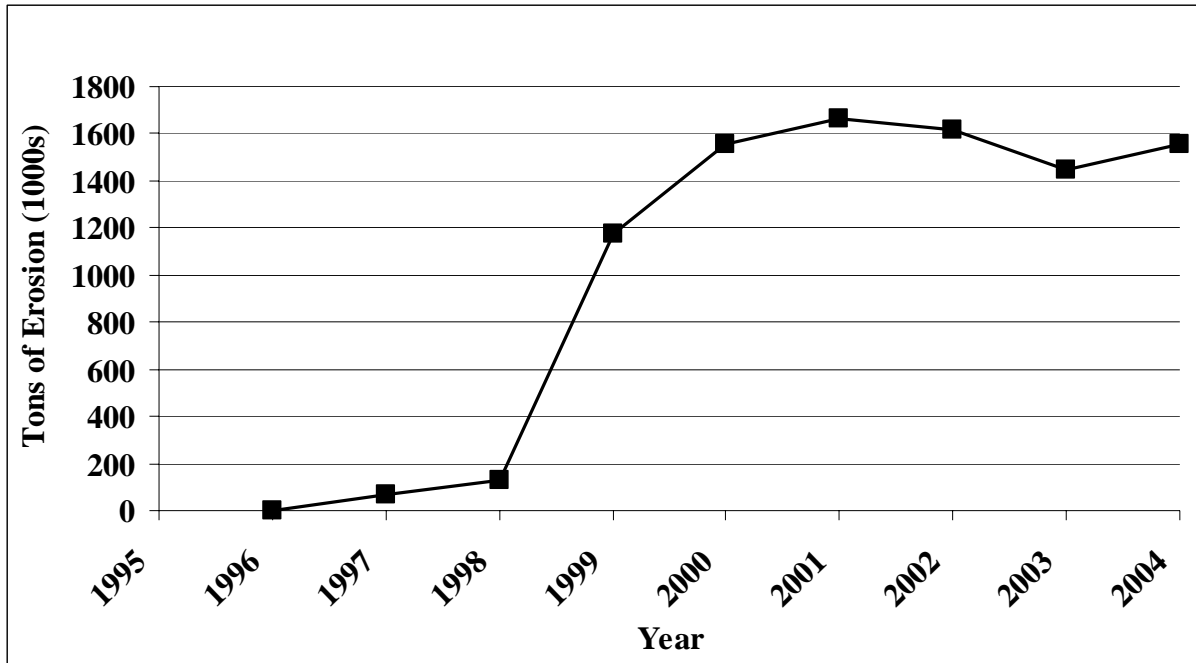
<sup>c</sup> Numbers in parentheses below parameter estimates are asymptotic standard errors.

<sup>d</sup> Elasticities are calculated using the sum of the coefficients for RAIN and DRAIN at the mean of RAIN.

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



**Figure 1.** Estimated Acres of Herbicide-Resistant, No-Tillage, and Other Conservation-Tillage Cotton that Would Have Been Planted in Conventional-Seed and Conventional-Tillage Practices without the Synergistic Relationships among Seed and Tillage Technologies



**Figure 2.** Estimated Tons of Soil Erosion on Tennessee Cotton Land that Would Have Occurred without the Availability of Herbicide-Resistant Cotton Seed