

# Simultaneous Diffusion of Herbicide Resistant Cotton and Conservation Tillage

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This study used state-level data from 1997-2002 to econometrically estimate factors explaining the diffusion of two technologies by US cotton producers: herbicide-resistant (HR) cotton seed varieties and conservation tillage. A simultaneous equation model is estimated to examine complementarities between the two technologies. Based on results from a three-stage least squares model, the null hypothesis that diffusion of one technology is independent of diffusion of the other is rejected. Elasticities calculated at sample means indicate that a 1% increase in a state's adoption rate for HR cotton increases the state's adoption rate for conservation tillage by 0.48%. A 1% increase in the adoption rate of conservation tillage increases the adoption rate of HR cotton by 0.16%.

**Key words:** herbicide resistance, conservation tillage, adoption, diffusion, cotton, seeds, biotechnology.

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## Introduction

This study addresses three primary research questions. First, does diffusion of herbicide-resistant (HR) cotton seed varieties encourage diffusion of conservation tillage? Second, does diffusion of conservation tillage practices encourage diffusion of HR cotton? Third, what other economic, institutional, or agronomic factors explain diffusion of each technology?

Conservation tillage practices preserve at least 30% of residue from the previous crop on fields. Conservation tillage involves less intensive field tillage and fewer passes across the field. Specific practices include mulch till (where soil is disturbed prior to planting), ridge till (where residue is left between tilled ridges) and no-till (where no tillage is carried out). Conservation tillage can reduce soil erosion and attendant water pollution. By reducing erosion, it can maintain the long-term productivity of soils. It can also increase soil carbon sequestration (Sandretto & Payne, 2006). Conservation tillage can form part of conservation plans that growers are required to adopt on highly erodible land (HEL) (Claassen, 2006). Under law, growers are required to adopt conservation compliance plans on HEL to be eligible for some farm program benefits.

Traditionally, intensive tillage has been the main means of weed control (Carpenter & Gianessi, 1999). In the 1970s, the introduction of post-emergence herbicides provided growers with more weed control options throughout the growing season. The introduction of HR seed varieties in the mid 1990s, primarily Roundup® Ready glyphosate-resistant seed varieties, allowed growers to spray glyphosate over the top of crops, killing weeds without causing crop damage. Glyphosate is a broad-spec-

trum herbicide with a relatively long window of effectiveness during the growing season. The rapid adoption of HR cotton and soybean varieties has been attributed to the greater flexibility in weed management they afford growers (Carpenter & Gianessi, 1999; Marra, Piggott, & Carlson, 2004).

Amid controversies about the environmental impacts of transgenic crop varieties and widespread use of glyphosate, there is also the possibility that transgenic, HR seed varieties and conservation tillage are complementary. This suggests that adoption of HR seed could have environmental benefits of reducing soil erosion, water pollution, and carbon emissions. This latter effect could come both from soil carbon sequestration and from the fact that conservation tillage (especially no-till) entails less fuel for tilling passes across the field (Brookes & Barfoot, 2006). Some studies have explicitly considered how adoption of HR seeds and conservation-tillage practices complement each other. Fulton and Keyowski (1999) introduce a theoretical model illustrating how the returns to adopting HR canola increase with relative reliance on conservation tillage methods. Carpenter and Gianessi (1999) discuss complementarities between HR seed varieties and conservation tillage in soybean production. Ward, Flanders, Isengildina, and White (2002) applied data-envelopment analysis to data from Georgia cotton growers to evaluate the allocative and technical efficiency of production with transgenic seed varieties and conservation tillage. They concluded that "Roundup Ready technology is better utilized with conservation tillage than with conventional tillage" (p. 12). These studies focus on how adoption of one technology affects incentives to adopt the other.

Several studies have noted that there are higher rates of conservation tillage adoption on acres planted to HR seed varieties (Carpenter, Gianessi, Sankula, & Silvers, 2002; Fawcett & Towery, 2002; Fernandez-Cornejo & Caswell, 2006; Kim & Quinby, 2003; Marra et al., 2004; Trigo & Cap, 2003). Although HR seeds and conservation tillage appear correlated, correlation does not necessarily imply causation. For example, Fernandez-Cornejo et al. (2003) pointed out that many growers had already adopted conservation tillage prior to the introduction of HR soybean varieties.

Finally, some studies have explicitly considered the issue of causality, attempting to estimate econometrically how adoption of seed varieties affects tillage practices and vice versa. Kalaitzandonakes and Suntornpithug (2003) considered simultaneous adoption of conservation tillage, HR cotton, Bt cotton, and stacked-trait (HR and Bt) cotton. Adoption was measured as the percent of cotton acres planted to a seed variety and percent of acres following conservation tillage practices. Analyzing multi-state, cross-section data from individual cotton farms, they used the generalized method of moments (GMM) to correct for potential simultaneity bias. In their simultaneous model, they found adoption of conservation tillage increased adoption of HR cotton varieties and adoption of stacked trait varieties. They also found that adoption of HR and stacked-trait varieties increased adoption of conservation tillage.

Roberts, English, Gao, and Larson (2006) examined trends in aggregate adoption of conservation tillage and HR cotton varieties in Tennessee between 1992 and 2004. They estimate a simultaneous equation system where the dependent variables were  $\ln(HR/100 - HR)$  and  $\ln(CT/100 - CT)$ , where  $HR$ =percent acres planted to herbicide-resistant cotton and  $CT$ =percent cotton acreage practicing conservation tillage. Using three-stage least squares (3SLS) estimation, Roberts et al. (2006) found that the proportion of acreage planted to one technology had a positive influence on acreage planted to the other. They also reported cross-adoption elasticities. Evaluated at sample means, the elasticity of HR cotton adoption with respect to conservation tillage adoption was 1.74, while the elasticity of conservation tillage adoption with respect to HR cotton adoption was 0.24.

Fernandez-Cornejo and McBride (2002) and Fernandez-Cornejo et al. (2003) considered simultaneous adoption of HR soybean varieties and no-till using farm-level data for 1997. Their specification considered only impacts on no-till and did not consider adoption of ridge

or mulch tillage. In simultaneous probit models, they found that adoption of conservation tillage increased the probability of adopting HR varieties, but that adoption of HR varieties did not have a significant effect on adoption of conservation tillage. They also tested for endogeneity of practices in each equation, using Wu-Hausman tests. While they rejected the hypothesis that HR seed adoption was an exogenous regressor in the conservation-tillage equation, they failed to reject the exogeneity of conservation tillage in the HR seed-adoption equation. Consequently, in subsequent research, Fernandez-Cornejo, Klotz-Ingram, and Jans (2002b) examined adoption of HR soybeans as a function of conventional tillage adoption, treating tillage choice as exogenous. They found that adoption of conventional tillage (as opposed to conservation tillage) reduced the probability of adopting HR soybean seeds.

## Methods

The studies of Kalaitzandonakes and Suntornpithug (2003), Fernandez-Cornejo and McBride (2002), and Fernandez-Cornejo et al. (2002b, 2003) considered the adoption choice of individual growers at a single point in time. Roberts et al. (2006) considered aggregate adoption over time in a single region. This study considers the joint diffusion of HR cotton seed varieties and conservation tillage across both space and time. To estimate factors affecting the simultaneous diffusion of HR cotton and conservation tillage, a two-equation simultaneous system was specified and estimated using three-stage least squares methods. The approach allows us to perform classical hypothesis tests on the independence of the diffusion of each technology.

The proportion of acres planted to HR cotton in state  $i$  in year  $t$ ,  $HR_{it}$  is represented as a logistic function

$$HR_{it} = K_i / [1 + \exp(-a_i - b_{it}t - u_{it})]. \quad (1)$$

The term  $a_i$  characterizes the initial rate of HR cotton adoption in state  $i$  in the first year it is available (or the initial year data is available). The term  $K_i$  is an adoption ceiling defining the maximum proportion of acreage that will ultimately be planted to HR cotton. The term  $b_{it}$  determines how quickly the rate of HR cotton adoption moves from the initial adoption level to the adoption ceiling, while  $u_{it}$  is an error term. The term  $t$  is a time trend. As time passes ( $t$  gets larger), adoption rates increase then decrease. This produces the classic S-shaped diffusion curve (Figure 1). Griliches (1960, pp. 275) noted that this specification

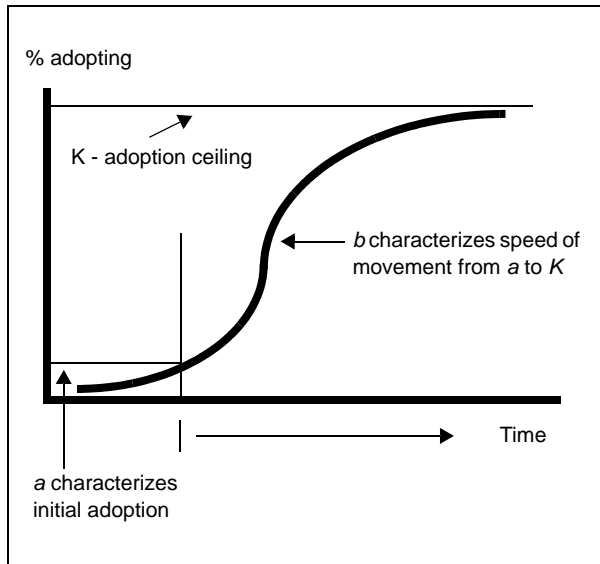


Figure 1. Logistic diffusion curve.

“[a]llows us to summarize large bodies of data on the basis of three major characteristics (parameters) of a diffusion pattern: the date of beginning (origin), relative speed (slope), and final level (ceiling).”

Griliches was interested in answering three basic questions. Why did some areas begin using hybrid corn before others? Why did hybrid corn spread faster in some areas than in others? Why did some areas reach higher adoption ceilings than others? He related regional differences to differences in the origin (*a*), speed (*b*), and ceiling (*K*). He characterized *a*—the origin parameter—as capturing the date of availability of hybrid corn and depending on the supply of suitable seed. He hypothesized that seed suppliers would focus seed development and marketing in areas where they could make the most profits. These would be in larger markets, ones where gains from adoption were larger, or both. Another factor was whether experiment stations had developed new seed lines well-adapted to local conditions.

While Griliches discussed *a* in terms of supply-side factors, *b* measured the rate of acceptance of the new seed varieties by producers. The speed of adoption (*b*) should increase with the profit advantage of the new technology. A new technology with a greater profit advantage would have a larger value for *b* and would diffuse more rapidly (Figure 2). Differences in the adoption ceiling *K* could be explained by differences in the average profit gain from adoption and that, except for

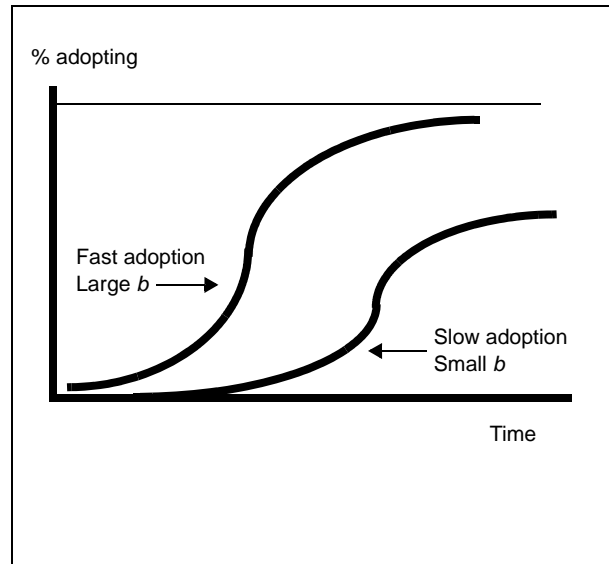


Figure 2. Effect of *b* on diffusion rate.

marginal production areas, a common, fixed ceiling would perform quite well.

The proportion of cotton acres where conservation tillage is practiced in state *i* in year *t*,  $CT_{it}$  can also be represented as a logistic function:

$$CT_{it} = Z_i / [1 + \exp(-c_i - d_{it}t - v_{it})]. \quad (2)$$

The term  $c_i$  characterizes the rate of conservation tillage adoption in state *i* in the initial year of the study. The term  $Z_i$  is an adoption ceiling defining the maximum proportion of acreage where conservation tillage is practiced. The term  $d_{it}$  determines how quickly the rate of conservation tillage adoption moves from the initial adoption level to the adoption ceiling, while  $v_{it}$  is an error term.

If adoption ceilings  $K_i$  and  $Z_i$  for HR cotton and conservation tillage are assumed to equal one (maximum adoption rates of 100%), then Equations 1 and 2 can be re-written as

$$\ln [HR_{it} / (1 - HR_{it})] = a_i + b_{it}t + u_{it} \quad (3)$$

$$\ln [CT_{it} / (1 - CT_{it})] = c_i + d_{it}t + v_{it} \quad (4)$$

The terms,  $a_i$ ,  $b_{it}$ ,  $c_i$ , and  $d_{it}$  in turn can be treated as functions of economic, institutional, or agronomic variables. Because parameters of the diffusion process change over time, this type of model has been called a dynamic diffusion model (Fernandez-Cornejo, Alexan-

der & Goodhue, 2002a; Knudson, 1991). The origin parameters can be expressed as the functions

$$a_i = a_0 + a_1 PARENT + a_2 CALAW \quad (5)$$

$$c_i = c_0 \quad (6)$$

where  $a_0$ ,  $a_1$ ,  $a_2$ , and  $c_0$  are regression parameters to be estimated. The variables *PARENT* and *CALAW* represent supply-side factors that affect availability of HR cotton seed. The HR trait was initially bred into a subset of cotton varieties. *PARENT* measures the proportion of cotton acreage planted to these recurrent parent varieties in 1996, the year before HR cotton became commercially available. Widespread adoption of recurrent parent lines implies that these lines were relatively well-adapted to local growing conditions. *PARENT* is meant to capture the extent to which the new HR cotton varieties, first available in 1997, were adapted to local conditions. Adopting a new HR cotton variety based on a previously adopted recurrent parent minimized the risk of adopting a new technology, as other aspects of the seed remain the same (or approximately the same). Producers familiar with the original seed variety could then switch more easily to a new HR seed variety based on the recurrent parent.

The other variable *CALAW* is a dummy placed in the model to measure the effects of the One-Variety Law in place since 1925 in California. This law allowed only the Acala variety of cotton seed to be planted in the San Joaquin Valley in an attempt to better market California cotton. This law, however, was repealed in 1999. This law presented a supply-side restraint on the availability of HR cotton for California growers. We have no prior hypotheses about factors that would cause the supply of conservation tillage practices or information to vary by state, so the origin variable is treated as a simple parameter to be estimated,  $c_0$ .

The rate of acceptance parameters  $b_{it}$  and  $d_{it}$  can be expressed as functions of other variables

$$b_{it} = b_0 + b_1 \ln[CT_{it}] + b_2 COTPRICE_{it-1} + b_3 \ln[GLYPHPRICE_{it-1}] + b_4 HARVESTPC_i \quad (7)$$

$$d_{it} = d_0 + d_1 \ln[HR_{it}] + d_2 COTPRICE_{it-1} + d_3 PRECIP_i + d_4 LANDVALUE_{it} + d_5 PCHEL_{it} \quad (8)$$

where  $b_0$ ,  $b_1$ ,  $b_2$ ,  $b_3$ ,  $b_4$ ,  $d_0$ ,  $d_1$ ,  $d_2$ ,  $d_3$ ,  $d_4$ , and  $d_5$  are regression parameters to be estimated. The variables  $\ln[CT_{it}]$  and  $\ln[HR_{it}]$  are the natural logs of the conservation tillage and HR cotton adoption rates. By includ-

ing these variables in Equations 7 and 8, one can directly test the effect conservation tillage adoption has on HR cotton adoption and vice versa.

The variable  $COTPRICE_{it-1}$  is the real (inflation-adjusted) price of cotton received by growers in a state, lagged one year. We hypothesize that higher cotton prices should encourage more rapid diffusion of technologies. The variable  $\ln[GLYPHPRICE_{it-1}]$  is the log of the ratio of the price of glyphosate to the US Department of Agriculture (USDA) herbicide price index, lagged one year. Fernandez-Cornejo et al. (2002a) included this variable in an earlier study of HR cotton diffusion. They expected that—because HR cotton seed and glyphosate are complementary—the regression coefficient would have a negative sign. In their regression, however, the coefficient was positive.

The variable  $HARVESTPC_i$  is the historic average from 1985-1995 of total harvested cotton acres as a percentage of total planted cotton acres in the state. We hypothesize that adoption will proceed more quickly in states that harvest a greater proportion of their planted acreage (i.e., areas with lower rates of crop failure and abandonment). The reasoning is as follows. When producers purchase HR cotton seed they must pay a premium for the seed that ranges from \$7.48 to \$19.02 per acre, depending on the region (Carpenter et al., 2002). This up-front cost can only be recouped if the harvested crop provides higher returns than non-HR cotton. Thus, the expected pay-off to adoption is lower in areas with greater risk of crop failure or abandonment (i.e., a low value of  $HARVESTPC$ ). As a historic average, this variable is also predetermined.

The variable  $PRECIP_i$  is average precipitation over the period 1950-1994 for each state, weighted by harvested crop land, while  $PCHEL_i$  is the percent of highly erodible land (HEL) in a state in 1997. Both precipitation and highly erodible soils are associated with greater soil erosion. In these areas one would expect there to be greater returns to soil-conserving practices such as conservation tillage. USDA conservation compliance requirements may also require growers to adopt soil-conserving practices on HEL as a condition for receiving commodity program payments.

In a study of farm-level conservation tillage adoption, Soule, Tegene, and Wiebe (2000) found that adoption rates were lower in rapidly urbanizing areas. Soule et al. (2000) argued that proximity to urban areas could impede adoption, as farmland may be converted to urban use in the near future. So, growers would have less economic incentive to adopt practices to maintain the long-term productivity of soils. To capture the rela-

tive influence of urbanization at the state level, we use  $LANDVALUE_{it}$ , the average sales value of cropland in each state. Cropland converted to residential or commercial real estate often sells for significantly more money than cash rental rates for land used in farming would imply. Thus, high sales prices are used as a proxy variable to measure development pressure.

Inserting Equations 5 and 7 into Equation 3 and Equations 6 and 8 into Equation 4 yields

$$\begin{aligned} \ln [HR_{it} / (1 - HR_{it})] = & a_0 + a_1 PARENT + a_2 CALAW \\ & + t \{ b_0 + b_1 \ln[CT_{it}] + b_2 COTPRICE_{it-1} \\ & + b_3 \ln[GLYPHPRICE_{it-1}] + b_4 HARVESTPC_i \} \\ & + u_{it} \end{aligned} \quad (9)$$

$$\begin{aligned} \ln [CT_{it} / (1 - CT_{it})] = & c_0 + t \{ d_0 + d_1 \ln[HR_{it}] \\ & + d_2 COTPRICE_{it-1} + d_3 PRECIP_i \\ & + d_4 LANDVALUE_{it} + d_5 PCHEL_{it} \} \\ & + v_{it} \end{aligned} \quad (10)$$

Equations 9 and 10 represent a simultaneous system where diffusion of one technology affects the diffusion of the other technology. The null hypothesis that the technologies spread independently can be tested, by testing the hypothesis that  $b_1 = d_1 = 0$ .

Two problems can arise estimating Equations 9 and 10 separately using ordinary least squares (OLS) methods. First, the error term  $u_{it}$  represents unobserved factors affecting the diffusion of HR cotton, such as the distribution of grower characteristics, environmental or economic conditions, or other state-specific factors. Yet, one would expect that such factors that affect choice of HR cotton would also affect choice of conservation tillage. If true, this would mean that the variable  $t \ln[CT_{it}]$  and the error term  $u_{it}$  in Equation 9 are correlated. This violates a standard assumption of OLS estimation, and parameter estimates would be biased and inconsistent. The same problem could hold for  $t \ln[HR_{it}]$  and the error term  $v_{it}$  in Equation 10. Second, the error terms  $u_{it}$  and  $v_{it}$  could also be correlated, so separate estimation may not yield efficient parameter estimates. To correct for both these problems, three-stage least squares (3SLS) estimation was carried out on Equations 9 and 10 (Greene, 2003; Kennedy, 1979).

The lagged price of cotton is the only predetermined, exogenous control variable included in both Equations 9 and 10. We assume that variables affecting the supply of seed ( $CALAW$  and  $PARENT$ ) only enter the HR seed diffusion equation. We also assume that diffusion of glyphosate-resistant seed is affected directly by the price of

glyphosate and the percent of a state's planted crop that has been harvested, averaged over the previous ten years, while diffusion of conservation tillage is not directly affected by these variables. Likewise, we assume that our measure of development pressure ( $LANDVALUE$ ) affects incentives for long-term soil conservation (and hence enters the tillage-choice equation), but does not affect annual seed choice directly. Precipitation and the extent of highly erodible land are also assumed to affect tillage, but not seed choice directly.

## Data

The data on the percent of cotton acreage managed with conservation tillage were collected from the Conservation Technology Information Center's (CTIC) *National Crop Residue Management Survey: Conservation Tillage Data* (CTIC, n.d.). A total of 64 observations for 16 cotton-producing states were collected for each year from 1997 to 2002, except for the years 1999 and 2001; CTIC did not conduct surveys for these years.

Data on the yearly percent of total cotton acres planted to HR cotton from 1997 to 2002 for each state in this study were collected from the National Center for Food and Agricultural Policy (NCFAP; Carpenter et al., 2002), from the *California Cotton Review* (Vargas & Wright, 1998), and from *Cotton Varieties Planted* published by the USDA's Agricultural Marketing Service (USDA AMS, various years).

The total number of cotton acres planted yearly from 1997 to 2002 and the yearly upland cotton prices for each state were obtained from the website of the National Agricultural Statistical Service of the United States Department of Agriculture (USDA NASS, various years) under the heading *State Level Data for Field Crops: Oilseeds and Cotton*. The data for planted and harvested cotton acreage for each state were gathered from the USDA NASS website under the heading *Crops by State* (USDA NASS, 2004). Data on the adoption of a recurrent parent cottonseed were collected from *Cotton Varieties Planted* published by the USDA AMS (various years).

The data on the price of glyphosate in dollars per gallon and the USDA herbicide price index were obtained from *Agricultural Prices*. The price of glyphosate is divided by the herbicide price index based on the 1990-1992 dollar value of herbicide. The log of the ratio was lagged one year. The annual price of upland cotton per pound for each state was obtained from the USDA NASS database *State Level Data for Oilseeds*

**Table 1. Descriptive statistics for untransformed regression variables.**

Variable	Mean	Standard deviation	Minimum	Maximum
<i>year</i>	3.25	1.94	1.00	6.00
<i>HT_percent</i>	0.37	0.34	0.01	0.99
<i>CT_percent</i>	0.19	0.14	0.01	0.53
<i>precipitation</i>	3.44	1.26	0.84	4.79
<i>price</i>	0.55	0.18	0.26	0.82
<i>HEL</i>	0.29	0.26	0.03	0.89
<i>urban</i>	1954.39	1425.01	548.00	6167.62
<i>CA78</i>	0.03	0.18	0.00	1.00
<i>parent</i>	22.59	21.46	1.08	54.66
<i>harvest</i>	0.96	0.04	0.86	1.00
<i>Roundup</i>	43.93	4.15	39.73	48.46

and Cotton (various years). This price is then divided by the implicit price deflator of the Gross Domestic Product published by the US Department of Commerce Bureau of Economic Analysis (BEA, various years) in the *National Income and Product Account Tables*. The average cropland value data are published in USDA NASS's *Agricultural Land Values* (various years). The USDA herbicide price index and price of glyphosate in dollars per gallon were collected from the USDA NASS (various years) publication *Agricultural Prices*.

Data on monthly precipitation by harvested cropland acreage were collected from the *Weather Data* set compiled by the Economic Research Service (ERS) of the USDA (USDA ERS, 1950-1994). The erodibility index for cropland by state for the year 1997 on non-federal land was obtained from the USDA's Natural Resource Conservation Service (USDA NRCS, 2000). The index assigns a number (the t value) from 1 to 15 according to the erodibility of the soil. HEL includes cropland with a t-value of 8 and above.

Table 1 presents descriptive statistics for (untransformed) explanatory variables used in the regression equations.

## Results

Based on results from the 3SLS model, the null hypothesis that diffusion of one technology is independent of diffusion of the other is strongly rejected (Table 2). The coefficient for conservation tillage adoption is positive and significant at the 0.1% level in the HR cotton equation. Likewise, the coefficient for HR cotton adoption is positive and significant at the 0.1% level in the conservation tillage equation.

**Table 2. Three-stage least squares regression results: Diffusion of conservation tillage and HR cotton.**

Variable name	Conservation tillage diffusion equation	HR cotton diffusion equation
	Parameter estimate	Parameter estimate
	(t statistic) <sup>a</sup>	(t statistic)
<b>Origin variables</b>		
<i>Intercept</i>	-1.55 (-4.06)	-6.43 (-10.55)
<i>PARENT</i>		2.12 (3.35)
<i>CALAW</i>		-9.92 (-11.75)
<b>Acceptance variables</b>		
<i>YEAR ( t )</i>	-0.86 (-3.14)	-7.47 (-1.71)
<i>tCOTPRICE</i>	0.07 (0.48)	0.47 (2.13)
<i>tln(HR)</i>	0.19 (4.99)	
<i>tln(CT)</i>		0.11 (3.84)
<i>tPRECIP</i>	0.25 (7.13)	
<i>tLANDVALUE</i>	-0.0001 (-3.00)	
<i>tPCHEL</i>	0.94 (6.53)	
<i>tGLYPHPRICE</i>		1.86 (1.60)
<i>tHARVESTPC</i>		2.79 (2.88)
<b>Individual equation R<sup>2</sup></b>	0.57	0.82
<b>System R<sup>2</sup></b>	0.96	

<sup>a</sup> Critical values for t statistic, two-tailed test: 10% |t| = 1.645, 5% |t| = 1.96, 1% |t|=2.326, 0.1% |t| = 2.576.

We conducted Wu-Hausman endogeneity tests on each regression separately. The hypothesis that HR seed adoption was exogenous in the conservation tillage equation was rejected (P-value=0.0003). This suggests single equation, OLS estimates of conservation tillage with HR seed adoption as a regressor would yield biased and inconsistent parameter estimates. In contrast, we failed to reject (at the 5% level) the hypothesis that conservation tillage adoption was an exogenous regressor in the HR seed equation (P-value=0.15). These results are similar to Cornejo et al. (2003) who found that tillage choice was exogenous in an HR-soybean-seed equation,

while HR seed adoption was an endogenous regressor. Unlike Cornejo et al., however, our results suggest that HR seed adoption does significantly increase adoption of conservation tillage.

In both equations, the coefficient for cotton price is positive (indicating that higher cotton prices encourage adoption). But, the coefficient is only statistically significant for HR cotton adoption. In the HR cotton adoption equation, both the technology availability variables, *PARENT* and *CALAW*, are significant at the 0.1% level with expected signs. HR cotton diffusion also appears to proceed faster in states where a higher proportion of planted acres are harvested. This result is consistent with those of Kalaitzandonakes and Suntornpithug (2003), who found that percent of acres irrigated had a positive effect on HR-cotton seed adoption. The ratio of planted to harvest cotton is much higher on irrigated than dryland cotton. The coefficient on the relative price of glyphosate to other herbicides is insignificant, though positive. This result is counterintuitive but similar to that found by Fernandez-Cornejo et al. (2002a). Further research is needed to see if there is a problem with the construction of this particular price index or whether the index does not capture the costs of using glyphosate accurately.

In the conservation-tillage equation, diffusion proceeds faster in states with a higher proportion of HEL and with greater precipitation on cropland. This suggests that states with greater potential for erosion and possibly greater erosion-control regulatory requirements have adopted conservation more quickly. Over the study period, conservation tillage has spread less rapidly in states with higher sales values for cropland. If higher land values are picking up effects of urbanization and development pressure, this suggests that development pressure may reduce long-run incentives for soil conservation.

It is possible to calculate cross elasticities of adoption for the two technologies. The elasticity of conservation tillage adoption with respect to HR cotton adoption  $e_{CH}$  measures the percentage change in the conservation tillage adoption rate for a 1% increase in the HR cotton adoption rate. Likewise, the elasticity of HR cotton adoption with respect to conservation tillage adoption  $e_{HC}$  measures the percentage change in the HR cotton adoption rate for a 1% increase in the conservation tillage adoption rate. These elasticities can be written as

$$e_{HC} = t(1 - HR_{it}) b_1 \quad (11)$$

$$e_{CH} = t(1 - CT_{it}) d_1. \quad (12)$$

**Table 3. Cross-elasticities of adoption of HR seeds and conservation tillage.**

Elasticity of:	Evaluated at sample mean	Minimum sample value	Maximum sample value
Conservation tillage adoption with respect to HR seed adoption, $e_{CH}$	0.48	0.13	1.14
HR seed adoption with respect to conservation tillage adoption, $e_{HC}$	0.16	0.01	0.46

Equations 11 and 12 show that the percentage increase in adoption of one technology in response to a percent change to adoption of the other technology is not constant, but diminishes as adoption rates increase. For example, the effect of conservation tillage on HR seed adoption falls to zero as HR seed adoption reaches 100% in a state. This specification makes certain intuitive sense. If adoption of HR seeds approaches 100% (as it has in some states), there is simply little room for further percentage increases in adoption rates.

Evaluating these elasticities at sample means, a 1% increase in a state's adoption rate for HR cotton increases the state's adoption rate for conservation tillage by 0.48% ( $e_{CH}=0.48$ ) (Table 3). This value ranges from 0.13% to 1.14% across sample observations. Similarly, a 1% increase in the adoption rate of conservation tillage increases the adoption rate of HR cotton by 0.16% ( $e_{HC}=0.16$ ), with a range of 0.01% to 0.46% across sample observations. Low values at the lower bound for this elasticity stem from the fact that adoption of HR seeds is quite high (reaching 99%) in some states.

## Conclusions

Previous research has examined

- joint adoption of conservation tillage and transgenic, HR seeds using farm-level, cross-section data (Fernandez-Cornejo et al., 2002b, 2003; Fernandez-Cornejo & McBride, 2002; Kalaitzandonakes & Suntornpithug, 2003);
- aggregate adoption of both technologies over time for a single state (Roberts et al., 2006); or
- diffusion of HR seeds only across regions and time (Fernandez-Cornejo et al., 2002a).

This study extends this earlier work by considering the simultaneous spatial and temporal diffusion of conservation tillage and HR seeds among cotton growers. We extend a dynamic diffusion model by allowing for the

possibility that diffusion of one technology may affect diffusion of the other.

Results suggest the two technologies are complementary and mutually reinforcing. Diffusion of conservation tillage speeds diffusion of HR seeds and vice versa. Elasticities calculated at sample means indicate a 1% increase in a state's adoption rate for HR cotton increases the state's adoption rate for conservation tillage by 0.48%. A 1% increase in the adoption rate of conservation tillage increases the adoption rate of HR cotton by 0.16%.

The Griliches-type model that characterizes technology diffusion in terms of origin, speed, and ceiling performed quite well. Adoption rates of HR seeds were higher in states with higher rates of prior adoption of the non-transgenic recurrent parents of HR seed varieties. This is consistent with Griliches' (1960) earlier conjecture that supply of seeds adapted to local conditions spurs adoption. California's One Variety Law was found to slow the adoption of HR seeds.

Diffusion of conservation tillage was faster in states with a higher percentage of highly erodible land and greater precipitation. States with greater potential for erosion and possibly greater erosion-control regulatory requirements have adopted conservation more quickly. Conservation tillage has spread less rapidly in states with higher sales values for cropland. If higher land values are picking up effects of urbanization and development pressure, this suggests that development pressure may reduce long-run incentives for soil conservation.

Conservation tillage offers various agronomic and environmental benefits. These benefits include enhanced soil quality, reduced flooding, more beneficial soil microbes, reduced fossil fuel use, soil carbon sequestration, reduced sediment and chemical runoff reaching water bodies, and reduced generation of particulate matter (Fawcett & Towery, 2002). Because of such environmental benefits, there has been interest in the extent to which transgenic, herbicide resistant seed varieties encourage conservation tillage and the degree to which these seed and tillage technologies are complementary. Our results suggest that, at least for cotton, the two technologies are indeed complementary. Diffusion of herbicide resistant cotton seeds was found to speed diffusion of conservation tillage, while diffusion of conservation tillage sped diffusion of herbicide resistant cotton seed varieties.

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