Revisiting the Impact of Bt Corn Adoption by U.S. Farmers

Jorge Fernandez-Cornejo and Seth Wechsler

This study examines the impact of adopting Bt corn on farm profits, yields, and insecticide use. The study employs an econometric model that corrects for self-selection and simultaneity. The model is estimated using nationwide farm-level survey data for 2005. Regression analysis confirms that Bt adoption is associated with increased variable profits, yields, and seed demand. However, the results of this analysis suggest that Bt adoption is not significantly related to insecticide use. This result may be due to the fact that insect infestation levels were lower in 2005 than they were in previous years.

Key Words: genetically engineered corn, insect resistance, Bt corn, insecticide use, technology adoption, yields

Genetically engineered (GE) crop varieties with enhanced pest management traits, such as insect resistance and herbicide tolerance, are being adopted by U.S. farmers at a very rapid rate.[1] Insect-resistant crops (Bt crops) contain a gene from a soil bacterium, *Bacillus thuringiensis* (Bt), which produces a protein that is toxic to specific insects. Bt corn with traits to control the European corn borer was introduced commercially in 1996 (Hyde et al. 1999). By the year 2000, Bt corn accounted for 19 percent of corn-planted acres. Bt corn with traits to control corn rootworms was commercially introduced in 2003. By 2010, Bt corn accounted for approximately 63 percent of domestic corn acres (Figure 1).

Estimating the costs and benefits associated with Bt corn use is complicated by the high degree of variability in regional factors such as weather, infestation levels, and seed costs. Moreover, the impact of Bt adoption is often confounded with the effect of other production practices such as crop rotation. Several studies have analyzed how Bt corn affects pesticide use, yields, costs, and profits (Duffy 2001, McBride and El-Osta 2002, Fernandez-Cornejo and McBride 2002, Pilcher et al. 2002, Baute, Sears, and Schaafsma 2002, Dillehay et al. 2004, Fernandez-Cornejo and Li 2005, Mungai et al. 2005, Fang et al. 2007). Generally speaking, these studies have found that Bt corn yields are higher for adopters than for growers of conventional varieties (Table 1). For example, Duffy (1999) found that Bt corn yields were approximately 13 bushels per acre higher than conventional yields. Mitchell, Hurley, and Rice (2004) found that adoption increased yields by 2.8 to 6.6 percent. Dillehay et al. (2004) found that adoption increased yields by 5.5 percent in Pennsylvania and Maryland. Fernandez-Cornejo and Li (2005) found that, on average, adopters had 12.5 bushels per acre higher corn yields than non-adopters. Several studies also concluded that adopters used less insecticide than non-adopters (Table 1).

However, most studies have analyzed data collected in the first years of adoption. As a recent report by the National Research Council (NRC) (NRC 2010) suggests, "The environmental, economic, and social effects on adopters and non-adopters of GE crops [have] changed over time...."

Corn farmers have experienced significant changes in market and environmental conditions since the turn of the twenty-first century. For instance: (i) corn borer infestations have decreased dramatically (Hutchinson et al. 2010); (ii) new

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[1] Crops with insect resistance and herbicide tolerance traits are classified as first generation GE crops. First generation GE crops include crops with enhanced input characteristics.

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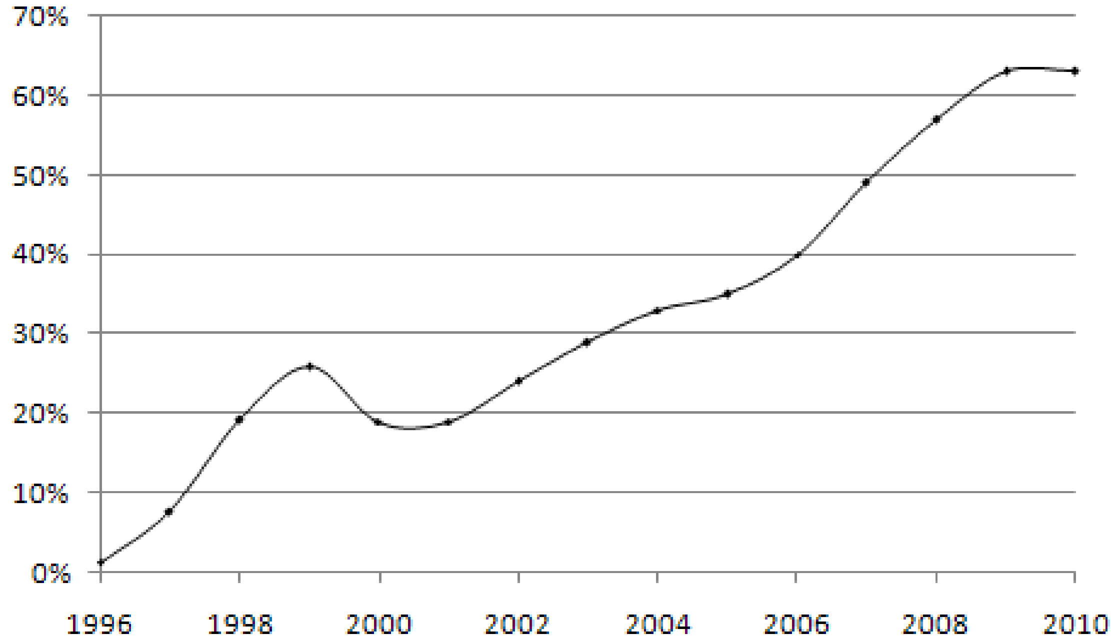

Figure 1. Bt Adoption Rates for U.S. Corn Farmers (1996–2010)

Source: NASS/ERS ARMS data, the NASS Objective Yield Survey, and the NASS June Agricultural Survey.

traits, such as corn rootworm resistance (introduced in 2003) and corn earworm resistance (introduced in 2010) have been engineered into Bt seeds; and (iii) average corn prices, as well as most input costs, have increased.

One would expect decreases in pest populations to slow rates of Bt adoption. As Figure 1 demonstrates, there was a decrease in adoption rates between 1999 and 2002. However, adoption rates rose from 2003 onwards. This may be because farmers placed a premium on the new (insect-resistance) traits that have been incorporated into Bt seeds since 2003. Alternately, increases in expected profits may have made these seed purchases more palatable.

Given that pest populations have dwindled and that new insect-resistance traits have been incorporated into Bt seeds, one might expect a reduction in the profitability of insecticide use. This would lead to a reduction of insecticide use and to a change in how Bt adoption affects insecticide use.

This paper analyzes farm-level data collected nationally in 2005 in an effort to understand how changes in market and environmental conditions have affected Bt adoption, farmers' profits, and farmers' input decisions. The study will provide an important counterpoint to research conducted during the earlier stages of Bt adoption.

As a recent report by the NRC (2010) concludes, "empirical research into the environmental and economic effects of changing market conditions and farmer practices have not kept pace [with the changes themselves]." This analysis addresses some of those concerns.

The Data

The data used in this study were obtained from the 2005 nationwide Agricultural Resource Management Survey (ARMS), which was developed and conducted by USDA. The ARMS survey has a multi-phase, multi-frame, stratified, probability-weighted design. In other words, farmers with specific characteristics are administered different phases of the ARMS survey during and after each survey year. After data collection, the National Agricultural Statistics Service (NASS) generates

Table 1. Summary of Select Studies on the Effects of Bt Corn on Yields, Insecticide Use, and Returns

		Effects on ...		
Researchers / Date of Publication	Data Source	Yields	Insecticide Use	Returns
Pilcher and Rice 1998 [a]	Survey	Increase	Decrease	Depends on infestation
Duffy 2001 [b]	Survey	Increase	N/A	Same
Baute, Sears, and Schaafsma 2002 [c]	Experiments	Increase	N/A	Depends on infestation
McBride and El-Osta 2002 [d]	Survey	N/A	N/A	Decrease
Pilcher et al. 2002 [e]	Survey	Increase	Decrease	N/A
Dillehay et al. 2004 [f]	Experiments	Increase	N/A	N/A
Mitchell, Hurley, and Rice 2004 [g]	Experiments	Increase	N/A	Depends on infestation
Fernandez-Cornejo and Li 2005 [h]	Survey	Increase	Decrease	N/A
Mungai et al. 2005 [i]	Experiments	Increase	N/A	N/A
Fang et al. 2007 [j]	Experiments	Increase	N/A	N/A

Note: N/A = not available.

[a] Results using data from surveys administered in 1996–1998.
[b] Results using data from surveys administered in 1998.
[c] Results using data from field trials administered in 1996–1997.
[d] Results using data from surveys administered in 1998.
[e] Results using data from surveys administered in 1996–1998.
[f] Results using data from field trials administered in 2000–2002.
[g] Results using data from field trials administered in 1997–1999.
[h] Results using data from surveys administered in 2001.
[i] Results using data from field trials administered in 2002–2003.
[j] Results using data from field trials administered in 2002.

probability weights to help ensure that the ARMS sample accurately represents the population of U.S. famers.

The ARMS survey has three phases. The ARMS Phase I survey is administered in the summer of the survey year. Phase I verifies that all respondents operate a farm or plant a specific crop. The ARMS Phase II survey is administered in the fall and winter of the survey year. This commodity-based, field-level survey collects data on production practices and input use. The ARMS Phase III is administered in the spring following the survey year. Phase III gathers data on debt, revenue, operating costs, and expenditures.

After merging the Phase II and Phase III datasets and excluding observations with missing values, 1,129 observations from 19 major corn-producing states were available for analysis.

According to the 2005 ARMS corn survey, 76.5 percent of the farmers adopting Bt corn indicated that they did so in order to increase yields. Other adopters reported that they used Bt corn to decrease pesticide costs (11.3 percent) or to save management time (3.3 percent). Approximately 10 percent of adopters reported using Bt corn for other reasons.

Survey results indicate that, on average (Table 2), actual corn yields were about 17 bushels per acre (12 percent) higher for adopters than for non-adopters, seed use was 0.02 bushels per acre (4.8 percent) higher for adopters than for non-adopters, insecticide use was 0.04 pounds of active ingredients per acre (43 percent) lower for adopters than for non-adopters, and variable profits were 18 dollars per acre (7.5 percent) higher for adopters than for non-adopters. Differences in the unconditioned means suggest that Bt adoption may increase variable profits, yields, and seeding rates, while decreasing insecticide use.

The geographical distribution of average corn yields and Bt adoption rates are shown in Figures 2 and 3, respectively.

Table 3 contrasts insecticide use in 2005 with insecticide use in 2001. Total pounds applied de-

Table 2. Sample Means and Definition of Main Variables—Corn Producers (2005)

Variable	Description	All Obs.	Bt Adopters	Non-Adopters
Yield	Per acre yields, in bushels	144.81	155.14	138.56
Seed use	Seed demand, in bushels per acre	0.35	0.36	0.34
Insecticide use	Insecticide demand, in pounds AI per acre	0.07	0.05	0.09
Bt corn	Dummy variable = 1 if the operator planted seeds with Bt traits	0.38		
Crop insurance	Dummy variable = 1 if the operator has crop insurance	0.76	0.88	0.68
Precipitation	Spring and summer precipitation, in meters	7.70	7.46	7.84
Seed price	Seed price, dollars per bushel	108.99	120.18	102.23
Corn price	Corn price, dollars per bushel	1.99	1.95	2.01
Operator experience	Years of operator experience	36.24	33.63	37.81
Heartland	Dummy variable = 1 if the operation is located in the ERS-designated Heartland region	0.68	0.74	0.65
Insecticide	Dummy variable = 1 if insecticides are applied	0.20	0.22	0.19
Number of observations		1,129	435	694

Source: 2005 ARMS Corn Survey.

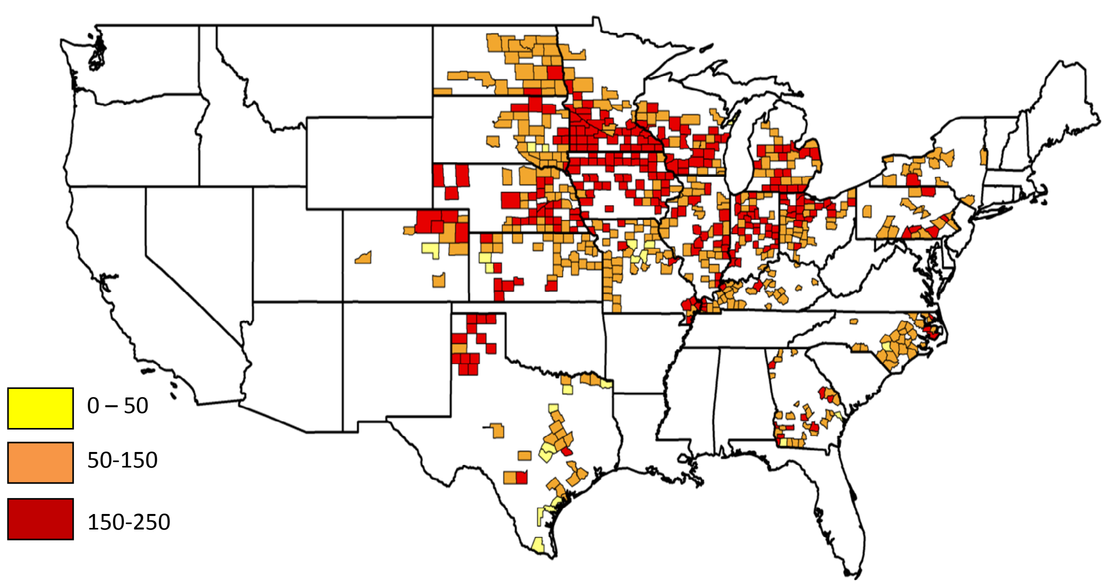

Figure 2. Average Corn Yields (in bushels per acre)

Source: NASS/ERS 2005 ARMS corn data.

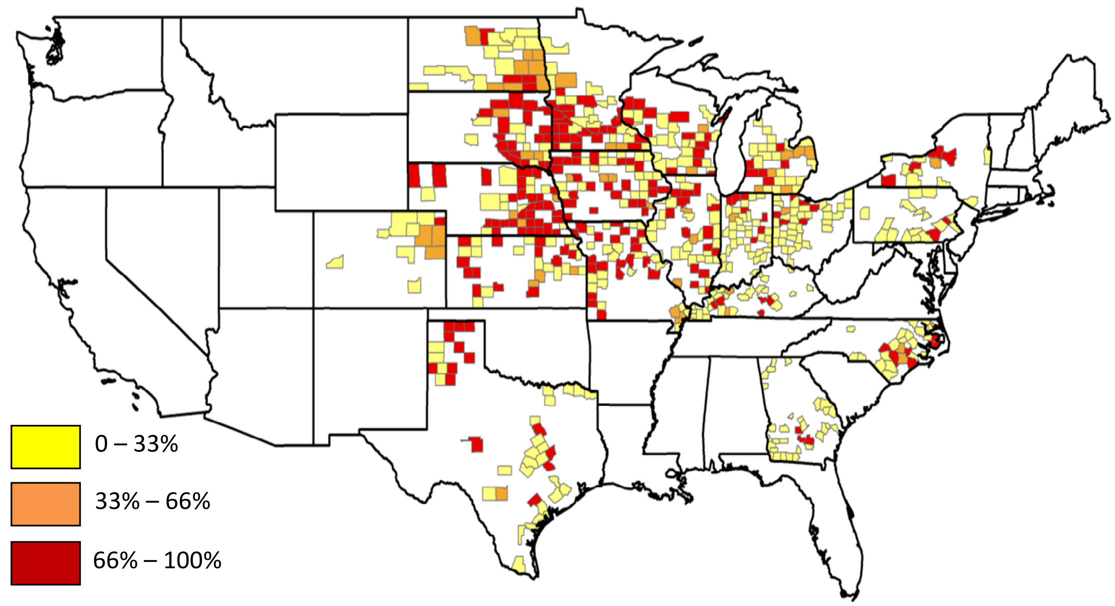

Figure 3. Percentage of Respondents that Adopted Bt Corn Seeds
Source: NASS/ERS 2005 ARMS corn data.

clined by approximately 4.5 million pounds (or 50 percent) over this time period. Usage declined most for Chlorpyrifos and Terbufos. Chlorpyrifos and Terbufos are used to control corn rootworms and other insects (Wilson et al. 2005).[2] Given that Bt corn can be used to control the European corn borer (since 1996) and the corn rootworm (since 2003), it is likely that the decreased demand for corn insecticides is due to Bt adoption.

Mean comparisons are illustrative. However, definite conclusions should not be drawn from these comparisons unless the data is generated under carefully controlled experimental settings, where factors other than adoption are "controlled for" by making them as similar as possible (Fernandez-Cornejo and Li 2005, Fernandez-Cornejo and McBride 2002). Clearly, this is not the case with survey data. After all, Bt use is not random. In other words, surveyed farmers were not randomly assigned to a treatment group (adopters) and a control group (non-adopters). Consequently, adopters and non-adopters may be systematically different from one another (for example, in terms of management ability). This situation, called self-selection, biases the statistical results, unless it is corrected (Heckman 1979). For these reasons, we specify an econometric model that accounts for self-selection.

The Model

In this section, we briefly discuss the theoretical framework of the model and present the specifications used in the empirical analysis.

This study employs a two-stage framework. The first stage, which is referred to as the *adoption decision model,* is used to determine factors that influence a farmer's decision to use Bt seeds. The second stage, or *impact model,* is used to estimate the impact that adopting Bt seeds has on yields, seed demand, insecticide demand, and farm variable profits.

The Adoption Decision Model

Because adoption decisions involve a binary choice (experimenting with a new technology or retaining an old one), a probit specification is

[2] See http://www.chlorpyrifos.com/benefits-by-crop.htm.

Table 3. Major Insecticides Used on Corn (2001[a] and 2005[b])

	AREA APPLIED		TOTAL APPLIED	
	Percent		*Thousand Pounds*	
Active Ingredient	2001	2005	2001	2005
Bifenthrin	2	2	67	72
Carbofuran	*	*	476	113
Chlorpyrifos	4	2	3,663	2,047
Cyfuthrin	4	7	16	38
Dimethoate	*	*	164	68
Esfenvalerate	*	*	1	8
Fipronil	3	1	259	88
Lambda-cyhalothrin	2	1	23	25
Methyl parathion	1	*	386	82
Permethrin	3	1	236	116
Propargite	*	*	156	289
Tebupirimphos	4	6	371	573
Tefluthrin	6	7	466	637
Terbufos	3	*	2,491	331
Petroleum Distillate	*	N/A	56	N/A
Phorate	*	N/A	73	N/A
Zeta-cypermethrin	N/A	*	N/A	11
Other	N/A	N/A	100	351
Total			**8,904**	**4,498**
Planted acres (in thousands)			76,470	70,745

* Area applied is less than one percent.

[a] Planted acres in 2001 for the 19 program states were 70.7 million acres. States included are Colorado, Georgia, Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, New York, North Carolina, North Dakota, Ohio, Pennsylvania, South Dakota, Texas, and Wisconsin.

[b] Planted acres in 2005 for the 19 program states were 76.5 million acres. States included are Colorado, Georgia, Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, New York, North Carolina, North Dakota, Ohio, Pennsylvania, South Dakota, Texas, and Wisconsin.

Source: USDA (2002, 2006).

used in this stage of the analysis. Formally, if F denotes the normal distribution, the probability of adopting a seed with Bt traits is $P(I_{Bt} = 1) = F(\delta_{BT}Z)$, where I_{Bt} is an indicator for whether the farmer chooses Bt seeds, δ is a vector of parameter estimates, and Z is a vector of explanatory variables. The specification for the adoption equation is $I_{Bt} = \delta_{Bt}'Z + \varepsilon_{Bt}$, where the residuals, ε_{Bt}, are normally, identically, and independently distributed. Elements of Z include: (i) acres planted (as a proxy for farm size), (ii) operator experience, (iii) the relative price of Bt seeds, (iv) expected profits, (v) the debt to asset ratio, (vi) the percentage of corn grown under production or marketing contracts, (vii) crop insurance (which is used in many studies as a proxy for risk aversion), (viii) conservation tillage, (ix) irrigation, (x) crop rotation, (xi) operator knowledge about pest infestations, and (xii) an indicator for whether the farm is located in the region designated "Heartland" by USDA's Economic Research Service (ERS).

The Impact Model

The second stage of the model examines how Bt adoption affects pesticide use, yields, and variable profits. To do this in a manner consistent with farmers' optimization behavior, we use the well-developed restricted profit function (Diewert 1974). Using the Hotteling-Shephard lemma, we derive the output supply and input demand functions from the profit function.

For the empirical model, we use a normalized quadratic restricted profit function (Diewert and Ostensoe 1988). Considering land as a fixed input, imposing symmetry by sharing parameters, imposing linear homogeneity by normalization (using the price of labor as the numeraire), and appending disturbance terms, the per-acre profit function (π), the supply (yield) equation (Y), the per-acre demand equation for seeds (X_1), and the per-acre demand equation for insecticides (X_2) are:

$$(1)\quad \pi = A_0 + A_y P + \sum_j A_j W_j + \sum_k C_k R_k + 0.5 G_{yy} P^2 + \sum_j G_{yj} P W_j + \sum_k F_{yk} P R_k + 0.5 \sum_j \sum_i G_{ij} W_i W_j + \sum_k \sum_j E_{jk} W_j R_k + \varepsilon_\pi$$

$$(2)\quad Y = A_y + G_{yy} P + \sum_j G_{yj} W_j + \sum_k F_{yk} R_k + \varepsilon_y$$

$$(3)\quad X_1 = A_1 + G_{y1} P + \sum_j G_{1j} W_j + \sum_k E_{1k} R_k + \varepsilon_1$$

$$(4)\quad X_2 = A_2 + G_{y2} P + \sum_j G_{2j} W_j + \sum_k E_{2k} R_k + \varepsilon_2 ,$$

where j indexes inputs used in the production process (for instance, seeds and insecticides), k indexes exogenous variables describing farm-specific characteristics (for instance, operator education, farm location, etc.), P and W are normalized output and input prices (respectively), and A, C, E, F, and G are parameters (Fernandez-Cornejo 1996). The vector R contains a measure of Bt adoption (as discussed in the next section) as well as exogenous variables to control for pest infestation levels and management characteristics.

Self-Selection

As discussed in a previous section, since farmers are not randomly assigned to a treatment group and a control group, adopters and non-adopters may be systematically different from one another. If these differences affect both farm performance and Bt adoption, they will confound the analysis (Fernandez-Cornejo 1996). This is a classic case of self-selection (Greene 1997).

Self-selection is a type of endogeneity (Maddala 1983, Greene 1997). Endogeneity arises when there is a correlation between the explanatory variables and the model's residuals.[3] If endogeneity is not accounted for (for instance, through the use of instrumental variable techniques), the results of the analysis will be biased.

For simplicity, consider self-selection in the context of determining whether Bt adoption affects seed demand. Let the true model be:

$$(5)\quad X_{Seed_i} = \beta_1 S_i + \propto Bt_i + \gamma_1 RA_i + e_i$$

$$(6)\quad Bt_i = \beta_2 Z_i + \gamma_2 RA_i + v_i ,$$

where X_{Seed_i} represents seed use, $Bt_i \in \{0,1\}$ represents the farmer's decision to adopt Bt seeds, S_i and Z_i are vectors of (exogenous) explanatory variables, RA_i represents an unobserved variable (e.g., the farmer's desire to avoid risk), β_1, β_2, $\propto$, γ_1, and γ_2 are vectors of parameter estimates, and e_i and v_i are error terms.

RA is assumed to be unobserved. Thus, it is necessary to estimate:

$$(7)\quad X_{Seed\, i} = \beta_1 S_i + \propto Bt_i + \varepsilon_1 ,$$

where the error term is $\varepsilon_1 = (\gamma_1 RA_i + e_i)$,

$$(8)\quad Bt_i = \beta_2 Z_i + \varepsilon_2 ,$$

where the error term is $\varepsilon_2 = (\gamma_2 RA_i + v_i)$.

[3] The residuals represent "noise" generated by random processes, but also contain variation caused by all unspecified or unobservable variables.

Consider equation (7). Notice that neither $E[Bt_i, \varepsilon_1]$ nor $E[X_{Seed_i}, \varepsilon_1]$ equals 0 because RA_i influences both Bt adoption and seed demand [as specified in equations (5) and (6)]. This correlation is the source of the self-selection problem. Regressing equation (7) without accounting for this correlation will generate biased parameter estimates.

Controlling for Endogeneity / Self-Selection

There are several methods of controlling for self-selection. The approach used in this study (sometimes called an instrumental variables approach) is to calculate predictions of Bt_i (denoted by $\widehat{Bt_i}$) using the parameters estimated from equation (8) and to substitute these predictions into equation (7). Because the variables in Z_i are exogenous, $\widehat{Bt_i}$ is uncorrelated with e_i, and $\propto$ is an unbiased estimator.

Estimation

The Adoption Model was estimated using the weighted probit routines in *STATA* and *LIMDEP*. The Impact Model was estimated using the Conditional Mixed Process Module (cmp) developed for *STATA* by David Roodman (Roodman 2009).[4]

The CMP module fits Seemingly Unrelated Regression Models with normally distributed error terms. Unlike many of the SUR routines available in *STATA* or *SAS*, this program enables the estimation of mixed models, allowing linear, probit, ordered probit, multinomial probit, Tobit, interval regression, and truncated-distribution regressions to be jointly estimated within the context of a seemingly unrelated system of equations. For the purposes of this analysis, the profit, yield, and seed demand equations were assumed to have uncensored, linear specifications. Because approximately 80 percent of the farmers in the sample do not use insecticides, a tobit specification was used to model insecticide demand. As in the Adoption Model, a weighted least squares technique was used to estimate the Impact Model.

After estimating the Adoption and Impact Models using the full sample, the standard errors were reestimated using the delete-a-group jackknife method described in Kott (1998) and employed in other analyses of ARMS data (Fernandez-Cornejo, Hendricks, and Mishra 2005, Fernandez-Cornejo and Li 2005, Fernandez-Cornejo, Klotz-Ingram, and Jans 2002).[5] It is well known that standard errors estimated using the jackknife method are conservative, and "may underestimate the significance of variables under some circumstances" (Fernandez-Cornejo, Hendricks, and Mishra 2005). For this reason, standard errors were calculated using both the standard estimation procedure and the jackknife method. The p-values used in this analysis were calculated using the jackknifed standard errors.

Model Results

The Adoption Decision Model

Table 4 presents results from the Adoption Model. Most of these results corroborated *a priori* assumptions. For instance, previous work has established that large operations are more likely than small operations to adopt agricultural innovations (Feder, Just, and Zilberman 1985, Fernandez-Cornejo, Klotz-Ingram, and Jans 2002, Fernandez-Cornejo and Li 2005). Previous work has also established that farmers who purchase crop insurance are more likely than their uninsured counterparts to purchase Bt seeds (Fernandez-Cornejo and McBride 2002).[6] Similarly, it is well known that the opportunity cost of pest infestations tends to be higher on irrigated operations, operations in the heartland (which tend to have highly productive soils), and other operations with high expected yields. Finally, it is not surprising that farmers expecting yield losses from corn borers are more likely to adopt insect-resistant seeds. In other words, it was expected that the

[4] This module is based on work by Cappellari and Jenkins (2003), Gates (2006), Geweke (1989), Hajivassiliou and McFadden (1998), and Keane (1992, 1994).

[5] The National Agricultural Statistics Service (NASS) partitions the sample into 15 groups of observations. Fifteen "replicate" groups of observations are formed by excluding one of the 15 original groups from the full sample. NASS calculates sampling weights for the full sample, as well as each of the replicates. In order to estimate the model, parameter estimates are estimated using the full sample. To calculate the standard errors, the model is run 15 additional times (using each of the 15 subsamples and the appropriate replicate weights). The standard errors estimated from each subsample are saved and used to calculate the adjusted standard errors [see Fernandez-Cornejo, Hendricks, and Mishra (2005)].

[6] Bt seeds and crop insurance both reduce expected losses from pest infestations.

Table 4. Predicting Bt Adoption—Corn Producers (2005)

Observations :	1,129		
McFadden pseudo R-squared	0.15		

Variable	Parameter Estimate [a]	SE, Using Standard Method	SE, Using Jackknife Method
Constant	-1.03*	0.31	0.51
Acres planted	0.005***	0.001	0.002
Operator experience	-0.01**	0.003	0.004
Relative price of Bt seeds	-0.16	0.17	0.28
Expected profits [a]	-0.19	0.51	1.22
Debt to asset ratio	0.08	0.15	0.29
Contract	-0.04	0.22	0.36
Crop insurance	0.50**	0.11	0.17
Conservation tillage	0.04	0.09	0.20
Irrigation	0.74**	0.17	0.33
Crop rotation	0.07	0.15	0.29
Ind_Cbor	0.73***	0.12	0.19
Ind_Cwrm	-0.0002	0.12	0.20
Heartland	0.22	0.10	0.18

Note: *** indicates that P < 0.01, ** indicates that P < 0.05, and * indicates that P < 0.10.

[a] Variable Profits are used as a proxy for expectations

Source: Model results.

parameter estimates on *Size*, *Crop Insurance*, *Irrigation*, *Heartland*, and *Ind_cbor* would be positive.

While we expected the parameter estimate for operator experience to be positive, this parameter estimate was negative and significant.[7] One explanation is that changing perceptions about the probability of insect infestations have decreased the perceived value of Bt seeds. For instance, corn borer infestations have radically declined since the introduction of Bt corn (Hutchinson et al. 2010). This decline may be more apparent to experienced corn farmers (who are better at forecasting insect populations) than it is to inexperienced ones. In other words, experienced farmers may update their expectations more quickly than their less experienced counterparts.[8]

The Impact Model

The Impact Model fits the data relatively well. While it appears that there is no consensus regarding the best measure of "goodness of fit" for Mixed Process Models (Kramer 2005), pseudo R^2 or generalized R^2 statistics are good alternatives to traditional R^2 values.[9] As discussed in Magee

[7] A positive relationship between farming experience (measured in years) and Bt crop adoption is commonly found. However, a negative relationship is not unprecedented in the literature (see, for example, Matuschke and Qaim 2009).

[8] As suggested by an anonymous reviewer, we also included both experience and age in the adoption equation, but this inclusion caused a severe collinearity problem, leading us to drop the age variable.

[9] Pseudo R^2 values resemble traditional R^2 values in that they are bounded on the [0,1] interval and higher values indicate better model fit. However, these values cannot be interpreted as one would interpret a traditional R^2, because the parameter estimates were not calculated to minimize variance (rather they were calculated via maximum likelihood or an alternative, iterative method). Different methods of calculating pseudo R^2's can provide very different values.

(1990), there are many different methods of calculating alternatives to R^2 statistics, all of which provide slightly different values.

One possibility involves computing directly the sum of squared residuals and dividing them by the sum of squared means. While identical to the formula used to calculate the traditional R^2 value, it does not have the same interpretation:

$$\text{Generalized } R^2 = 1 - \frac{\text{SSE}}{\text{SSM}} = 1 - \frac{|e'e|}{|m'm|},$$

where e is an nxl matrix of residuals (with n = the number of observations in the system, and l = the number of equations in the system), m is an nxl matrix of the difference in means $(y - \bar{y})$, and $|e'e|$ represents the determinant of $e'e$. Using this measure, the Generalized R^2 of the model is 0.87.

Most of the results derived from the parameter estimates corroborate *a priori* expectations. Increases in seed prices decrease seed demand. Increases in corn prices increase per-acre supply (yields). Pest infestation is associated with decreased yields, while being located in the Heartland region and high precipitation rates are associated with increased yields (Table 5). Increases in insecticide prices appear to decrease seed demand.[10] This implies that seeds and insecticides are complements in the production process. However, our results appear to suggest that increases in insecticide prices increase insecticide demand. The positive relationship between insecticide prices and insecticide use is likely to be due to the fact that insecticide prices are highly correlated with pesticide potency and other measures of pesticide quality.

Insofar as the impact of Bt adoption is concerned, this study's findings suggest that Bt seed use increases variable profits, yields, and seed demand (Tables 5 and 6). More specifically, a 10 percent increase in the probability of adoption was associated with a 1.65 percent increase in variable profits, a 1.7 percent increase in yields, and a 1 percent increase in seed demand (Table 7).

In contrast to the findings reported in Fernandez-Cornejo and Li (2005) (which were based on 2001 data), this study finds that Bt adoption does not have a statistically significant impact on insecticide demand (Table 6). This result may be related to the fact that insect infestation levels were lower in 2005 than they were in 2001 (Hutchinson et al. 2010). Because infestation levels were low, most farmers applied substantially fewer insecticides in 2005 than they did in 2001.[11] In fact (as previously mentioned), 80 percent of the farmers in the sample did not use insecticides at all. This may have reduced the impact of Bt adoption on insecticide use. After all, farmers use insecticides only if treating pest infestations is expected to be profitable. In other words, farmers use insecticides only if infestation levels are above a certain threshold.[12] Below this threshold, Bt adoption should not affect insecticide use.

The lower infestation levels are also consistent with the findings recently published in *Science* (Hutchinson et al. 2010) that areawide suppression of European corn borer is associated with Bt corn, which has been used in increasing amounts since 1996. This suggests that Bt corn has benefited not only adopters but non-adopters as well by reducing pest populations.

Concluding Comments

This study estimates how adopting Bt corn affects variable profits, yields, seeding rates, and insecticide demand using an econometric model that corrects for self-selection and simultaneity. The model is estimated using 2005 national survey data.

Survey results indicate that, on average, variable profits were about $18 per acre higher for adopters than for non-adopters, corn yields were 17 bushels per acre higher for adopters than for non-adopters, seed demand was 0.02 bushels per acre higher for adopters than for non-adopters, and insecticide demand was 0.04 pounds of active ingredients per acre lower for adopters than for non-adopters. Differences in the unconditioned means suggest that Bt adoption increases variable profits, yields, and seeding rates, while decreasing insecticide use.

[10] Parameter restrictions ensure that G12 equals G21. This ensures that the effect insecticide prices have on seed demand is equivalent to the effect seed prices have on insecticide demand.

[11] Average insecticide use was 0.07 pounds per acre in 2005 (Table 1) compared with about 0.15 pounds per acre in 2001 (Fernandez-Cornejo and Li 2005).

[12] This threshold may differ for adopters and non-adopters.

Table 5. Results from the Impact Model, Corn Producers 2005: Derived Output and Input Equations

Variable	Parameter	Yield[a]	Parameter	Seed[a]	Parameter	Insecticides[a]
Corn price	Gyy	82.32***	Gy1	0.58***	Gy2	-1.22***
Seed price	Gy1	0.58***	G11	-0.008***	G21	0.001
Insecticide price	Gy2	-1.22***	G12	0.0007	G22	0.031***
Bt corn	Fy1	65.27***	E11	0.09***	E21	0.02
Other insect infestations	Fy2	-37.17**	E12	-0.011	E22	0.10
Ind_Cbor	Fy3	-13.26**	E13	-0.02*	E23	-0.04
Ind_Cwrm	Fy4	8.01	E14	0.005	E24	0.08*
Heartland	Fy5	21.86***	E15	0.024***	E25	-0.07
Precipitation	Fy6	1.16	E16	-0.002	E26	-0.002
Education	Fy7	-0.60	E17	0.02*	E27	0.05
Constant	Ay	82.78***	A1	0.27***	A2	-0.38**

[a] P-values were calculated using the jackknifed standard errors. *** indicates that P < 0.01, ** indicates that P < 0.05, and * indicates that P < 0.10.

Source: Model results.

Table 6. Results from the Impact Model, Corn 2005: Profit Equation

Variable	Parameter	Parameter Estimate[a]	SE, Using Standard Method	SE, Using Jackknife Method
Constant	A0	-2.14	0.98	1.60
Corn Price	Ay	82.78***	9.37	7.15
Seed price	A1	0.27***	0.03	0.03
Insecticide price	A2	-0.38**	0.12	0.17
Bt adoption	C1	-3.36**	1.17	1.46
Other insect infestations	C2	-0.25	0.81	1.34
Ind_cbor	C3	1.08*	0.46	0.57
Ind_cwrm	C4	-0.85**	0.38	0.37
Heartland	C5	0.21	0.31	0.35
Precip	C6	0.00	0.09	0.11
Education	C7	-1.02*	0.50	0.53
(Corn Price)^2	Gyy	82.32***	20.17	22.87
*Corn price*seed price*	Gy1	0.58***	0.09	0.09
*Corn price*insecticide Price*	Gy2	-1.22***	0.27	0.33
*Corn price*Bt Adoption*	Fy1	65.27***	13.40	13.86
*Corn price*other Insect Infestations*	Fy2	-37.17**	12.27	13.57
*Corn price*ind_cbor*	Fy3	-13.26**	6.25	5.88
*Corn price*ind_cwrm*	Fy4	8.01	5.46	6.00
*Corn price*Heartland*	Fy5	21.86***	4.29	6.06

cont'd.

Table 6. Results from the Impact Model, Corn 2005: Profit Equation (cont'd.)

Variable	Parameter	Parameter Estimate[a]	SE, Using Standard Method	SE, Using Jackknife Method
*Corn price*precip*	Fy6	1.16	0.84	0.82
*Corn price*education*	Fy7	-0.60	4.76	4.93
(Seed price)^2	G11	-0.01***	0.001	0.001
*Seed price*insecticide price*	G12	0.001	0.001	0.001
(Insecticide price)^2	G22	0.03***	0.01	0.01
*Seed price*Bt adoption*	E11	0.09***	0.02	0.02
*Seed price*other insect infestations*	E12	-0.01	0.01	0.01
*Seed price*ind_cbor*	E13	-0.02*	0.01	0.01
*Seed price*ind_cwrm*	E14	0.005	0.01	0.01
*Seed price*Heartland*	E15	0.02***	0.01	0.00
*Seed price*precip*	E16	-0.002	0.00	0.00
*Seed price*education*	E17	0.02*	0.01	0.01
*Insecticide price*Bt adoption*	E21	0.02	0.13	0.18
*Insecticide price*other insect infestations*	E22	0.10	0.06	0.11
*Insecticide price*ind_cbor*	E23	-0.04	0.06	0.09
*Insecticide Price*ind_cwrm*	E24	0.08*	0.04	0.04
*Insecticide Price*Heartland*	E25	-0.07	0.04	0.05
*Insecticide Price*precip*	E26	-0.0020	0.01	0.01
*Insecticide Price*education*	E27	0.05	0.06	0.08

[1] P-values were calculated using jackknifed standard errors. *** indicates that P < 0.01, ** indicates that P < 0.05, and * indicates that P < 0.10.

Source: Model results.

Table 7. Elasticities, Insect-Resistant Corn (2005)

Variable	Elasticity with Respect to the Probability of Adoption
Profit	0.165
Yield	0.171
Seed	0.097
Insecticide	NS

Note: NS = not significant.

Source: Model results.

Regression analysis confirms that Bt adoption is positively associated with increased variable profits, yields, and seeding rates. However, our results suggest that Bt adoption is not significantly related to insecticide use. This result appears to be related to the fact that insect infestation levels were lower in 2005 than they were in earlier years. The lower infestation levels are consistent with the findings published in *Science* that areawide suppression of European corn borer is associated with Bt corn use.

The implications of these results should be regarded carefully, and only within the constraints of this analysis. The economic impacts of adopting genetically engineered crops vary with pest infestations, seed premiums, and prices of alternative pest control programs. Future work will examine the impact of new genetically engineered corn varieties that began to be commercialized in the United States in 2010 and which could offer additional corn yield gains by providing multiple Bt proteins with several modes of action that may result in more comprehensive insect control.

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