Dynamic Diffusion with Disadoption: The Case of Crop Biotechnology in the USA

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Controversy over the use of genetically engineered (GE) crops may have induced some farmers to disadopt these seeds, making a traditional diffusion model inappropriate. In this study, we develop and estimate a dynamic diffusion model, examine the diffusion paths of GE corn, soybeans, and cotton, predict the adoption of those crops over the next two years, and explore the main determinants of the diffusion rate. Our estimates indicate that future growth of Bt crops will be slower or negative, depending mainly on the infestation levels of the target pests. Adoption of herbicide-tolerant soybeans and cotton will continue to increase, unless consumer sentiment in the United States changes radically.

Key Words: corn, cotton, diffusion of innovations, genetic engineering, pest management, soybeans

Many agricultural innovations follow a well-known diffusion process which results in an *S*-shaped diffusion curve, first discussed by sociologists (and introduced to economics by Griliches in 1957).[1] The diffusion of genetically engineered (GE) crops followed this process in 1996–99, and the static logistic model appeared to fit the data (see figure 1). More recently, however, the market environment—particularly the export market—suggests the use of traditional (static) diffusion methods may not be appropriate for examining the diffusion of this technology.

Increased concern, especially in Europe and Japan, regarding the safety of these crops has resulted in the development of segregated markets for "non-GE" crops. While these markets are still small, the evolving information regarding the demand for these crops suggests dynamic considerations are especially important for this particular adoption process.

This study has three objectives: (*a*) to examine the diffusion paths of GE crops, including corn, soybeans, and cotton; (*b*) to predict the adoption of GE crops over the next two years under different scenarios; and (*c*) to explore some of the determinants of the rate of diffusion.

Background

Genetic engineering refers to the genetic modification of organisms by recombinant DNA techniques. By a precise alteration of a plant's traits, genetic engineering facilitates the development of characteristics not possible through traditional plant breeding techniques. By targeting a single plant trait, genetic engineering can decrease the number of unintended characteristics that may occur with traditional breeding. The genetically engineered crops considered in this analysis include those with herbicide-tolerant and insect-resistant traits.

GE crops carrying herbicide-tolerant genes were developed to survive certain broad-spectrum herbicides. Previously, these herbicides would have

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[1] The *S*-shaped diffusion was first observed by the French sociologist Tarde in 1903. An early empirical diffusion study was conducted by rural sociologists Ryan and Gross (1943).

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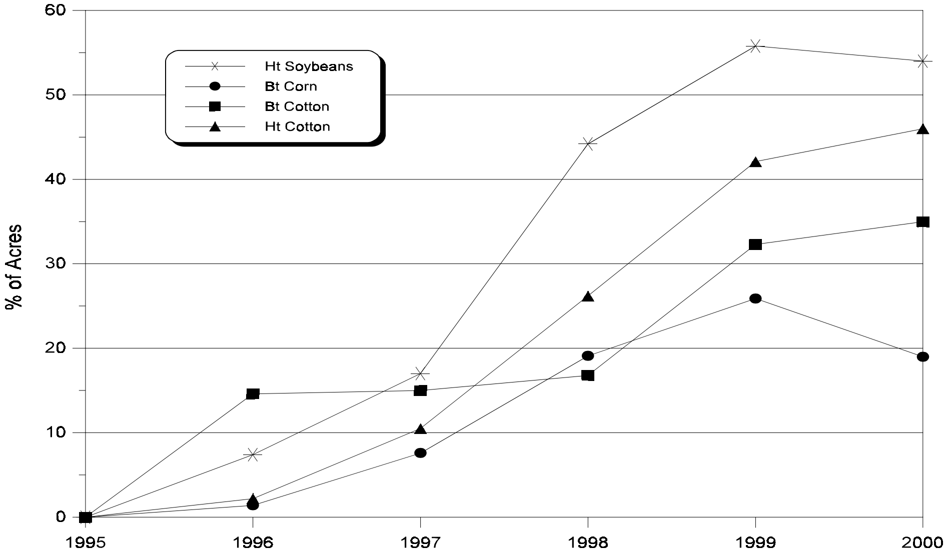

Sources: 1996–1998 data, Fernandez-Cornejo and McBride (2000), from ARMS data; 1999 data, USDA/NASS October Crop Production Survey, data for major states (USDA, 1999b), revised for coverage and planted acres; 2000 data, USDA/NASS Acreage Survey (USDA, 2000d).

Notes: Estimates for corn and cotton include acreage and production with stacked varieties (with both Bt and herbicide-resistant genes). Adoption for herbicide-tolerant soybeans for 1996–1999 includes seed obtained by traditional breeding but developed using biotechnology techniques that helped to identify the herbicide-resistant genes.

Figure 1. Adoption of GE crops in the USA, 1995–2000 (% of acres)

destroyed the crop along with the targeted weeds. Thus, herbicide-tolerant crops have provided farmers a broader variety of postemergent herbicides.

The most common herbicide-tolerant crops are Roundup Ready (RR) crops resistant to glyphosate, an herbicide effective on many species of grasses, broadleaf weeds, and sedges. Glyphosate tolerance has been incorporated into soybeans, corn, canola, and cotton. Other GE herbicide-tolerant crops include Liberty Link (LL) corn resistant to glufosinate-ammonium, and BXN cotton resistant to bromoxynil. [There are also traditionally bred herbicide-tolerant crops, such as corn resistant to imidazolinone (IMI) and sethoxydim (SR), and soybeans resistant to sulfonylurea (STS)].

Adoption of herbicide-tolerant soybeans has been particularly rapid compared to adoption of other agricultural innovations. Herbicide-tolerant soybeans became available to farmers for the first time in limited quantities in 1996; usage expanded from about 7% of the soybean acreage in 1996 to more than 50% in 2000. Similarly, herbicide-tolerant cotton expanded from around 2% of the cotton acreage in 1996 to 26% in 1998, and reached 46% in 2000 (figure 1).

Bt crops are the only insect-resistant GE crops commercially available. Bt crops are genetically engineered to contain a gene from the soil bacterium *Bacillus thuringiensis*, which produces a protein that is toxic when ingested by certain Lepidopteran insects. Crop varieties containing the Bt gene, such as corn and cotton, are able to produce this toxin, thereby providing protection against Lepidopteran insects.

Bt corn provides protection mainly from the European corn borer. The U.S. Environmental Protection Agency (EPA) approved Bt corn in August 1995, and its use grew from about 1% of planted corn acreage in 1996 to about 26% in 1999, before falling to 19% in 2000 (figure 1). Bt cotton is primarily effective in controlling the tobacco budworm, the bollworm, and the pink bollworm. Use of Bt cotton expanded rapidly, reaching 15% of cotton acreage in 1996 and about 35% in 2000 (figure 1).

Methodology

Early research on the adoption of innovations in agriculture focused on the diffusion process, i.e., after a slow start in which only a few farmers adopt the innovation, adoption expands at an increasing rate. Eventually, the rate of adoption decreases as the number of adopters begins to exceed the number of farmers who have not yet adopted. Finally, adoption asymptotically approaches its maximum level, until the process ends. This process results in an *S*-shaped diffusion curve.

As Griliches (1957) observes, the choice of functional form for the diffusion curve is somewhat arbitrary. The logistic function is often used to represent the *S*-shaped (sigmoid) diffusion process for agricultural innovations because of its relative simplicity (Griliches, 1957; Jarvis, 1981; Knudson, 1991; Karshenas and Stoneman, 1992). Other *S*-shaped functions used include the cumulative normal and the Gompertz model (Dixon, 1980). However, as Mahajan and Peterson (1985, p. 10) note, any unimodal distribution function will generate a (cumulative) *S*-shaped curve.

Diffusion curves are based on the notion that the current adoption rate is a function of the ultimate adoption level and the current adoption level:

(1) $dZ(t)/dt = f(K, Z, t)$,

where Z is the proportion of the total population that has adopted the innovation at time t, K is the ceiling value or long-run upper limit on adoption, and $dZ(t)/dt$ is the rate of diffusion at time t. Both K and Z are often expressed as a percentage of adopting units [usually percentage of firms, although in agriculture the percentage often refers to acreage under adoption (e.g., Knudson, 1991)].

It is common to assume the rate of diffusion $dZ(t)/dt$ is proportional to the difference of $K ! Z$. In this case, one obtains the so-called "fundamental diffusion model" (Mahajan and Peterson, 1985, p. 13):

(2) $dZ(t)/dt = g(t)[K ! Z(t)]$,

where $g(t)$ is denoted the coefficient of diffusion. Clearly, in this model as the adoption level increases and gets closer to the ceiling K, the diffusion rate decreases. If $g(t)$ is assumed to be constant, the resulting model is called the "external diffusion" model. If $g(t) = \mathrm{N}Z(t)$, the model is referred to as the "internal influence" model (Mahajan and Peterson, 1985, pp. 17–20), also known as the "contagion" or "epidemic" model in biology (Jaffe, Newell, and Stavins, 2000, p. 18) in which the innovation spreads as a disease. It is common to use the internal influence model in agricultural innovations. In this case, (2) explicitly becomes:

(3) $dZ(t)/dt = \mathrm{N}Z(t)[K ! Z(t)]$.

Integrating (2), we obtain the logistic:

(4) $Z = K/[1 + e^{(!a!\mathrm{N}t)}]$.

Making a log-linear (or logit) algebraic transformation of the adoption equation, we obtain $\ln[Z/(K ! Z)] = a + \mathrm{N}t$ (Griliches, 1957), where the slope parameter N is known as the natural rate of diffusion, rate of acceptance of the innovation, or rate coefficient (Griliches, 1957), as it measures the rate at which adoption Z increases with time. The parameter a is a constant of integration related to the extent of adoption at time 0, since at $t = 0$, $a = \ln[Z/(K ! Z)]$. The ceiling K is the long-run upper limit on adoption. Technically, the diffusion rate $dt(t)/dt$ approaches zero as Z approaches K [from equation (3)]. Also, K is the limit of Z as time tends toward infinity [equation (4)]. The logistic curve is symmetric around the inflection point (corresponding to the maximum adoption rate) at 50% of the ceiling level. The Gompertz model is similarly obtained from equation (3) simply by substituting the log of K and the log of $Z(t)$ for the two terms in braces and then integrating (Mahajan and Peterson, 1985, pp. 19–20).

Static and Dynamic Models

Static diffusion models, following the terminology of Knudson (1991), are growth models which represent the adoption path, expressing the percentage of adopters as a function of time. Such static models do not contain any other exogenous or endogenous factors. Two other characteristics of such models suggest their unsuitability for the type of innovations we consider here. First, they have a predefined point of maximum adoption as a share of the total population. Second, adoption must always increase over time until it converges to this maximum.

Knudson (1991) identifies the six basic assumptions of static diffusion models as follows: (*a*) an individual either adopts or does not adopt; (*b*) there is a fixed, finite ceiling K; (*c*) the rate coefficient of diffusion is fixed over time; (*d*) the innovation is not modified once introduced, and its diffusion is independent from the diffusion of other innovations; (*e*) one adoption is permitted per adopting unit, and this decision cannot be rescinded; and (*f*) a social system's geographical boundaries stay constant over the diffusion process. Many models have been used to study the diffusion of industrial innovations (Mahajan and Peterson, 1985, p. 30); for the case of agricultural innovations the most common model is the static logistic.

The static logistic is represented by equation (4), assuming N and K are constant (independent of t). In this case, the logit transformation of the adoption equation $\ln[Z/(K ! Z)] = a + \mathrm{N}t$ allows the use of linear regression analysis (Griliches, 1957). The main advantages of the static logistic are its ease of use and its wide applicability. It is also useful for forecasting because it requires no extra exogenous variables. Its usefulness is limited, however, because the parameters which determine the diffusion path are fixed over time.

Unlike static diffusion models, dynamic diffusion models allow the parameters of diffusion that determine the diffusion path (e.g., N, K) to change over time. Dynamic diffusion methods relax some of the assumptions of static diffusion models by allowing for disadoption and variations in the rate of acceptance (slope), and helping directly identify the variables significant to the adoption of an innovation.

In practice, two variations of dynamic models are often considered: the variable-ceiling logistic and the variable-slope logistic models. The variable-ceiling logistic defines the ceiling level (maximum rate of adoption) as a function of a vector $\mathbf{S}(t)$ of exogenous factors believed to influence adoption (Jarvis, 1981; Knudson, 1991). There are two drawbacks of the variable-ceiling logistic model. First, there is no assurance the ceiling will stay at theoretically justifiable levels, and second, there is no guarantee the equation will even converge when the data are extremely nonlinear.

The second version of the dynamic logistic model, the variable-slope logistic model, is obtained by allowing the adoption rate, rather than the maximum number of adopters, to vary as a function of exogenous factors like price, education, and so forth (Jarvis, 1981; Karshenas and Stonemann, 1992). This approach has several advantages. In this model the rate of acceptance (slope) can vary and even be negative, given the movement of the exogenous factors. It also allows the direct use of outside influences on adoption, and ceiling levels can be set at a theoretically justifiable level (e.g., 100% or lower). The variable-slope logistic model is easier to estimate and does not have the problems of the variable-ceiling logistic model for estimations using non-log-linear data (e.g., nonconvergence, unacceptable results such as K higher than 100%).

The Dynamic Logistic Model for the Diffusion of GE Crops

The diffusion of GE crops is modeled with a variable-slope logistic. According to Griliches (1957), the slope, or rate of diffusion, is largely a demand or "acceptance" variable, and differences in the slope are "interpreted as differences in the rate of adjustment of demand to a new equilibrium, and will be explained by variables operating in the demand side rather than by variables operating in the supply side" (p. 515).

For this reason, and to specify a parsimonious model, the slope N of the logistic is set equal to a function of two sets of variables (**R**, **S**) denoting demand conditions for GM crops. Thus we have: $\mathrm{N} = \mathrm{N}_0 + \mathrm{N}_1\mathbf{R} + \mathrm{N}_2\mathbf{S}$. Substituting the variable slope in (3), we obtain:

$$(5)\quad Z = K/\{1 + e^{[\,!\,a\,!\,(\mathrm{N}_0+\mathrm{N}_1\mathbf{R}+\mathrm{N}_2\mathbf{S})]t}\}.$$

Making the logit transformation and adding a vector of regional dummy variables (**D**) to account for regional technology differences (fixed effects, as we are using panel data) associated, for example, with the initial availability as well as the initial degree of promotion of the technology, and appending the error term g, we arrive at the estimating equation:

$$\begin{aligned}(6)\quad & \ln[Z/(K\ !\ Z)] \\ &= a + (\mathrm{N}_0 + \mathbf{N}_1\mathbf{R} + \mathbf{N}_2\mathbf{S})t + \boldsymbol{(}\mathrm{N}\mathbf{D} + \mathrm{g} \\ &= a + \mathrm{N}_0 t + \mathbf{N}_1\mathbf{R}t + \mathbf{N}_2\mathbf{S}t + \boldsymbol{(}\mathrm{N}\mathbf{D} + \mathrm{g}.\end{aligned}$$

The first set of variables (vector **R**) attempts to capture consumer preferences and/or concerns about GE products. These concerns are reflected in "market events" including, for example, labeling regulations for foods adopted by the European Union (EU), mandatory labeling proposals of genetically engineered foods by other countries such as Japan and Korea, announcements by UK food processors and supermarkets of plans to phase out use of biotech ingredients from their products, and plans by some U.S. food processors (Heinz, Gerber, Frito-Lay Inc.) and several Japanese brewers to stop using biotech ingredients in some of their products. Table 1 lists a summary of selected market events extracted from Dohlman, Hall, and Somwaru (2000).

Given the large number of "market events" (represented by the vector **R**) which have impacted the demand of GE crop products in recent years, and to conserve degrees of freedom, we specify a proxy for capturing most of the information contained in **R**. The proxy selected is an index of stock prices of agricultural biotech firms. Such an index was developed by Dohlman, Hall, and Somwaru (2000), who show empirically the effect of market events on equity values of agricultural biotechnology firms and justify their findings by the efficient markets/rational-expectations hypothesis, which "asserts that security prices immediately reflect all available

Table 1. Selected Market Events Correlated with the Index of Agbiotech Firms

Market Event	Date
< Press release details journal article finding that useful predatory insects could be harmed by Bt corn.	08/21/98
< EU labeling regulation no. 1139/98 enters into force.	08/31/98
< French court places injunction on growing/marketing of Bt corn.	09/25/98
< Greece bans import and sale of biotech rapeseed.	10/02/98
< Report released that biotech corn cross-pollinated adjacent field of conventional corn.	10/12/98
< UK supermarket ASDA asks suppliers not to use biotech corn or soybean ingredients in store brand products.	10/13/98
< French court upholds ban on three strains of Novartis Bt corn.	12/11/98
< Unilever UK, the Tesco supermarket chain, and Nestle UK announce plans to phase out use of biotech ingredients from their products.	04/27/99
< EU to freeze approval process for biotech corn developed by Pioneer. Commission states that already-approved products developed by Monsanto and Novartis could be affected.	05/20/99
< Journal *Nature* publishes report that pollen from Bt corn can harm monarch butterflies.	05/20/99
< Brazilian court upholds ban on biotech soybeans.	08/16/99
< Korean Minister announces plans for labeling foods with biotech ingredients.	11/22/99

Source: Dohlman, Hall, and Somwaru (2000).

information" (p. 4). Moreover, an earlier study by Bjornson (1998) confirmed that stock valuations of leading agricultural seed and biotechnology firms were increasingly being driven by the development of bioengineered crops.

An additional advantage of the stock-price index selected as a proxy for market events is that market events are incorporated into stock prices as soon as they occur, but translate into farmers' plantings/adoption decisions just once a year. In this context, the stock-price index assumes the role of a leading indicator of demand conditions (for example, an import ban occurring in November will be incorporated into stock prices immediately, but will only translate into planted acreages/adoption next year).

The second type of demand variable, **S**, is related to farmers' (marginal) cost decisions and depends on whether the technology provides insect resistance or herbicide tolerance. Since Bt crops replace chemical insecticides to control Lepidopteran insects, we use the average insecticide price as an explanatory variable for the rate of diffusion of Bt crops. Similarly, since most of the herbicide-tolerant crops imply the substitution of glyphosate for other herbicides, we include the price ratio of glyphosate to other herbicides as an explanatory variable for the rate of diffusion of herbicide-tolerant crops.

Regarding the effect of **R**, we expect an increase in the biotech stock price index (which reflects all known market events and consumer views about the agrobiotech products, thus acting as a leading indicator of the demand for those GE products) will predict an increase in the demand of genetically engineered crops. Consequently, the **R** term is expected to have a positive coefficient. For the crop-specific effects of **S**, an increase in insecticide price is expected to lead to an increase in the incentive to adopt insect-resistant crops, other factors constant. Similarly, an increase in the price of glyphosate relative to the price of other herbicides is expected to lead to a reduction in the use of glyphosate-tolerant crops.

Adoption Ceilings

We specify ceilings for the adoption of different genetically engineered crops by examining likely limitations to demand from either farm production considerations or market restrictions. The base-case ceiling values for Bt crops are computed by considering infestation levels and refugia requirements.

For Bt corn, the ceiling is calculated from past infestation levels of corn fields by the European corn borer (ECB), i.e., the percentage of corn acres infested with the European corn borer (at a treatable level) relative to planted corn acreage. Table 2 presents a summary of the results for major states for the 1997 crop year. The ceiling is computed by reducing the infested acreage by the refugia requirements. A 20% refugia, which is the figure most commonly recommended, was used in this study (Henderson, 1999; U.S. EPA, 1999).

Similarly, for Bt cotton, the ceiling is obtained from a three-year average of recent infestation levels

Table 2. Infestation of Corn Fields by the European Corn Borer: Area Infested at a Treatable Level, 1997 Crop Year (major U.S. states)

Region/State	Infested Area, Ha[a] (000s)	Planted Acres[b] (000s)	% of Acreage Infested
Heartland States:			
Illinois	50.0	11,200	
Indiana	140.9	6,000	
Iowa	2,840.9	12,200	
Minnesota	913.6	3,600	
Missouri	56.8	7,000	
Nebraska	1,400.0	2,950	
Ohio	58.0	9,000	
	5,460.2	51,950	25.96
Northern Crescent States:			
Michigan	40.9	2,600	
Pennsylvania	68.2	1,070	
Wisconsin	124.1	3,800	
	233.2	7,470	7.71
Prairie Gateway:			
Kansas	454.5	2,600	43.20
Other:			
Kentucky	34.5	1,150	
North Carolina	54.5	870	
North Dakota	77.3	590	
	166.3	2,610	15.70
Total:	**6,314.2**	**64,630**	**24.13**

[a] Data taken from Pike (1999).
[b] Data taken from USDA (1999b).

Table 3. Infestation of Cotton Fields by Bollworm, Budworm, and Pink Bollworm, 1996–98

Infestation/Year	Infested Acres[a] (000s)	Planted Acres[b] (000s)	% of Acreage Infested
Bollworm, Budworm:			
1996	10,249	15,024	68.22
1997	10,590	13,766	76.93
1998	9,052	13,653	66.30
Pink Bollworm:			
1996	486	15,024	3.23
1997	484	13,766	3.52
1998	304	13,653	2.23
All:[c]			
1996	10,735	15,024	71.45
1997	11,074	13,766	80.44
1998	9,356	13,653	68.53
3-Year Average:			**73.47**

[a] Data taken from Williams (1997, 1998, 1999).
[b] Data taken from USDA (1999b).
[c] Assuming no overlap.

of cotton fields, i.e., the percentage of cotton acres infested by the bollworm, budworm, and pink bollworm. The results are shown in table 3. This ceiling is also reduced by the refugia requirements.

Table 4. Total Exports as a Percentage of U.S. Production, 1995/96–1998/99 Crop Years

	Crop Year			
Crop/Description	1995/96	1996/97	1997/98	1998/99
Corn (million bushels):				
Production	7.400	9.233	9.207	9.759
Exports	2.228	1.797	1.504	1.981
Percent	30.1	19.5	16.3	20.3
Soybeans (million bushels):				
Production	2.177	2.380	2.689	2.741
Exports	0.851	0.882	0.873	0.801
Percent	39.1	37.1	32.5	29.2

Source: USDA (2000c).

Alternative scenarios for both Bt corn and Bt cotton are obtained assuming infestation levels 30% higher and 30% lower than the base case (past infestations).

For the case of herbicide-tolerant crops, a ceiling computed from weed infestation levels is not likely to be binding, since most acreage is potentially susceptible to infestation.[2] For this reason, ceilings in these cases are based on other considerations. For the diffusion of herbicide-tolerant soybeans, the ceilings are computed based on potential demand restrictions in the export market.

As soybean exports have represented around 35% of U.S. production in recent years (table 4), we examined four scenarios considering different percentages of U.S. exports for which GE soybeans remained eligible. In one extreme case, it was assumed all U.S. soybean exports would be of conventional crops. The other extreme case assumed no restrictions in exports of GE soybeans. Intermediate cases of export reductions of GM soybeans were also examined. As food-safety and consumer concerns in the export market are not expected to be very restrictive for herbicide-tolerant cotton, we follow Rogers (1983) and use a ceiling of 90% adoption. A 70% ceiling is used to examine the sensitivity of the results to the ceiling specification for our estimates.

To summarize, the estimation of the dynamic logit regression (for the base cases) is based on the following ceiling specifications: the ceiling for the diffusion of Bt corn is computed from the ECB infestation level adjusted by refugia requirements; the ceiling for the diffusion of Bt cotton is obtained

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[2] We do not consider export restrictions for Bt corn, since any such restrictions will be *less* binding than those implied by actual ECB susceptibility and/or infestation levels (compare table 2 regarding corn borer infestations to table 4 regarding the importance of corn exports).

Table 5. Definitions of Variables Used in the Dynamic Logit Model

Variable	Definition
TIME	Time in years, 1995 = 0
HEARTLAND	Dummy variable, =1 for the Heartland region, 0 otherwise
NCRESCENT	Dummy variable, =1 for the Northern Crescent region, 0 otherwise
PGATEWAY	Dummy variable, =1 for the Prairie Gateway region, 0 otherwise
MISSPORTAL	Dummy variable, =1 for the Mississippi Portal region, 0 otherwise
SOUTHSEABOARD	Dummy variable, =1 for the Southern Seaboard region, 0 otherwise
EUPLANDS	Dummy variable, =1 for the Uplands region, 0 otherwise
FRUITFULR	Dummy variable, =1 for the Fruitful Rim region, 0 otherwise
PBINDEX	Index of stock prices
PINSECT	Insecticide price index
PGLYPHERB	Price ratio of glyphosate to other herbicides
PBINDEX$t	Interaction term equal to the product of *PBINDEX* and *TIME*
PINSECT$t	Interaction term equal to the product of *PINSECT* and *TIME*
PGLYPHERB$t	Interaction term equal to the product of *PGLYPHERB* and *TIME*

from the infestation level of bollworms and budworms, adjusted by refugia requirements; the ceiling for herbicide-tolerant soybeans is calculated assuming no exports of GE soybeans. Finally, the ceiling for the diffusion of herbicide-tolerant cotton is set at 90%. We reestimate the model for a set of alternative ceiling values (scenarios).

Data and Estimation

Adoption data for 1996–98 are obtained from the Agricultural Resource Management Study (ARMS) conducted through on-site interviews by the National Agricultural Statistics Service (NASS) of the U.S. Department of Agriculture. More recent data are obtained from two other NASS surveys: the Crop Production Survey (commonly known as the objective yield survey), and the Acreage Survey. The Crop Production Survey was used to obtain adoption data for 1999 (USDA, 1999b), and the Acreage Survey provided adoption data for 2000 (USDA, 2000d). The crops included in the surveys are corn, soybeans, and upland cotton. The traits considered are herbicide tolerance and insect resistance (Bt). In the case of crops (cotton and corn) with staked genes, such as insect-resistance (Bt) and herbicide-tolerance traits, we include the percentage of adopters of staked genes in each of the categories.

A summary of the extent-of-adoption results using the ARMS data is shown in figure 1. The unit of observation in this study is farm resource region i ($i = 1, ..., 8$) at time t ($t = 1, ..., 5$). The analysis uses the new set of eight farm-resource regions depicting geographic specialization in production of U.S. farm commodities, recently constructed by the Economic Research Service (ERS) (USDA/ERS, 1999). To estimate the prices of chemical inputs (glyphosate, other herbicides, insecticides) expected by farmers at time of planting, we use the actual prices paid lagged one year, obtained from the USDA (2000a, e, f).

The stock price index of agbiotech firms is calculated by constructing an equally weighted portfolio of the following agricultural biotech firms (or their predecessors or successors): Pharmacia, Aventis, Astra-Zeneca, Novartis, Dupont, Dow, Delta and Pine Land, Hoecsht, Hoecsht Schering AgrEvo, Astra, Mycogen, Dekalb, and Pioneer Hi-Bred (Dohlman, Hall, and Somwaru, 2000).[3] The index is deflated by the S&P500 index and lagged one year.

Maximum-likelihood methods are used to estimate each of the regressions.[4] Time t is defined as the calendar year minus 1995 (so that time equals one for the first year of commercial adoption). Definitions of the variables used in the model are provided in table 5.

Weighted least squares estimation techniques are used to correct for heteroskedasticity because data are available in aggregate form (states, regions). The dynamic logit model was estimated under several scenarios of ceilings for each crop/technology using data for the period 1996–2000. Comparing the scenarios provides us with a measure of the sensitivity of our results to the precise ceiling specification.

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[3] For some multinational, multiproduct firms (e.g., Aventis, Dupont), revenues from GE seeds represent only a portion of their business. For these firms, stock prices may not be a very effective proxy for expectations in the market of GE seeds. For this reason, we have included a portfolio of 12 firms, several of which are seed and agbiotech firms (e.g, Delta and Pine Land, Pioneer, Mycogen, Dekalb), and we have given each firm the same weight regardless of its size. Moreover, even large multiproduct firms experienced stock price changes stemming from events in the GE demand. For example, a January 25, 2001, *New York Times* article reported, "... with the stock in the doldrums because of its struggles with agricultural biotechnology, Monsanto [and many other firms] ..." are severing agricultural biotech activities from their other businesses (e.g., Monsanto IPO) (Eichenwald, 2001, p. A1).

[4] Following the suggestion of an anonymous reviewer, we also used an alternative procedure in which we estimated the diffusion of Bt cotton and herbicide-tolerant cotton technologies together using the seemingly unrelated regression (SUR) framework.

Table 6. Dynamic Logit Parameter Estimates–Base Cases

Variable	Parameter Estimate	Standard Error	*t*-Value	Pr > |*t*|
A. Bt Corn (ceiling equal to ECB infestation adjusted by refugia requirements)				
Intercept	2.20398	3.35249	0.66	0.5274
TIME	!28.99758	16.79938	!1.73	0.1184
HEARTLAND	!0.87167	0.48001	!1.82	0.1028
NCRESCENT	!1.16932	0.71778	!1.63	0.1377
PGATEWAY	!2.88519	0.90590	!3.18	0.0111
PBINDEX$t	8.46688	3.01948	2.80	0.0206
PINSECT$t	13.28019	8.81819	1.51	0.1663
Adjusted $R^2 = 0.913$				
B. Bt Cotton (ceiling equal to infestation adjusted by refugia requirements)				
Intercept	0.09120	0.54888	0.17	0.8722
TIME	!7.46708	2.29334	!3.26	0.0116
MISSPORTAL	0.89482	0.33388	2.68	0.0279
SOUTHSEABOARD	0.93739	0.27486	3.41	0.0092
FRUITFULR	0.35130	0.33388	1.05	0.3235
PBINDEX$t	0.59192	0.28320	2.09	0.0700
PINSECT$t	4.82130	1.36198	3.54	0.0076
Adjusted $R^2 = 0.799$				
C. Herbicide-Tolerant Soybeans (ceiling calculated assuming no GE exports)				
Intercept	!3.89182	0.46479	!8.37	<0.0001
TIME	!0.81329	0.26627	!3.05	0.0080
HEARTLAND	!0.07828	0.14632	!0.53	0.6005
MISSPORTAL	0.20797	0.28968	0.72	0.4838
NCRESCENT	!0.36351	0.35074	!1.04	0.3164
PGATEWAY	0.59047	0.48103	1.23	0.2385
SOUTHSEABOARD	!0.64531	0.58688	!1.10	0.2889
EUPLANDS	0.87824	0.75083	1.17	0.2604
PBINDEX$t	!0.58520	0.62909	!0.93	0.3670
PGLYPHERB$t	3.13419	1.21704	2.58	0.0211
Adjusted $R^2 = 0.959$				
D. Herbicide-Tolerant Cotton (ceiling equal to 90%)				
Intercept	!17.48254	6.67041	!2.62	0.0278
TIME	2.13720	1.10169	1.94	0.0843
MISSPORTAL	0.16209	0.27624	0.49	0.5718
SOUTHSEABOARD	0.37307	0.26178	1.43	0.1879
PBINDEX$t	!0.55928	0.65087	!0.86	0.4125
PGLYPHERB$t	12.35018	6.19381	1.99	0.0773
Adjusted $R^2 = 0.953$				

Results

The results of the dynamic logit parameter estimates for Bt corn, Bt cotton, herbicide-tolerant soybeans, and herbicide-tolerant cotton are presented in table 6, panels A–D, for the base cases. The overall fit of the dynamic logistic model appears to be good. For the base cases, the adjusted R^2 ranges from 0.799 to 0.959.

The dynamic diffusion model appears to fit the data reasonably well for Bt crops. Further, the statistical significance of exogenous variables other than time in both equations suggests the use of a dynamic specification is warranted, rather than a static specification. In particular, the coefficients of the relevant market variables have the expected sign for Bt corn and Bt cotton. For both Bt crops (table 6, panels A and B), the diffusion rate is positively and significantly related to the biotech stock price index, confirming biotech stock prices do capture relevant agricultural market information and serve as a leading indicator of the acceptance/demand of biotech products. The rate of diffusion is also positively related to the price index of chemical insecticides, suggesting that the incentive to adopt the (substitute) Bt crops increases as insecticide prices rise. The price of insecticide is only significant, however, for Bt cotton.

The lack of significance of insecticide price for the adoption of Bt corn may be understood by noting that, in the absence of Bt corn, the European corn borer (ECB) is only partially controlled using chemical insecticides. The economics of insecticide use to control ECB are often unfavorable, and timely application is difficult. For these reasons, farmers often accept some yield losses rather than incur the expense of chemical insecticides to treat the ECB, and therefore do not view insecticides as a substitute for Bt corn adoption.

Contrary to our expectation, the adoption of herbicide-tolerant crops is positively and significantly related to the price ratio of glyphosate to other herbicides (table 6, panels C and D). This sign may have resulted from the many advantages of herbicide-tolerant soybeans perceived by growers, who rapidly increased their adoption of herbicide-tolerant soybeans between 1995 and 1998 despite moderate rising glyphosate prices (from about $54 to more than $56 per pound). This resulted in a positive correlation between glyphosate prices and adoption. Soybean growers continued increasing adoption while the glyphosate prices declined in 1999 and 2000 (glyphosate went off-patent in 2000), but this price decrease only affects the last year of data (2000) because we use expected (lagged) input prices in the model. Consequently, the effect of the negative correlation between prices and adoption in 2000 was weaker than that of the positive correlation of the previous four years, giving an overall positive sign.

For the herbicide-tolerant crops, the biotech stock price index is not significantly related to adoption, indicating planting decisions regarding these crops are not correlated with events driven by consumers' general concerns about genetically engineered crops. This, in turn, may be due to the fact that the majority of market concerns captured in the stock price index are related to Bt corn (refer to table 1), and in general most media coverage is related to Bt corn.[5]

Moreover, although corn and soybean growers are essentially the same individuals, planting decisions for Bt corn and herbicide-tolerant soybeans may vary due to differences in the risk-return profiles of the two GE crops, relative to conventional varieties (Alexander, Fernandez-Cornejo, and Goodhue, 2000b). In particular, the production advantages of herbicide-tolerant soybeans may outweigh any market risk due to consumer concerns about genetically engineered crops. For Bt corn, on the other hand, production benefits are not so large relative to market risk.

These results are supported by findings from focus groups and a survey related to planting decisions among Iowa corn-soybean farmers reported by Alexander, Fernandez-Cornejo, and Goodhue (2000a, 2001). Both the focus groups and the survey indicated that, unlike the case of Bt corn, planting decisions of most soybean farmers are not influenced by the GMO controversy.

Figures 2–5 show the diffusion paths for each crop and technique under the scenarios considered. The fit appears to be good, particularly for the base cases. Table 7 summarizes the results of the forecasts for each crop using the likely scenarios in each case and includes the 95% prediction intervals for each scenario. With the exception of 1999 Bt corn acreage, which was higher than predicted, the actual share of planted acreage was within the 95% prediction level for the base scenario for every crop-year observation. The sensitivity of 2001 and 2002 adoption levels to the specified adoption ceiling (scenarios) varies among technologies and crops.

As observed in table 7, Bt corn is relatively sensitive to the scenario (ceiling) specification. A corn-borer-infestation scenario 30% higher than that of the base case projects a Bt corn adoption level for 2001 corn acreage 15% above the base-case projection, while a 30% lower infestation projects a level 32% below the base-case projection. In contrast, the comparable numbers for Bt cotton are 4% and 3%, respectively. For herbicide-tolerant soybeans, the alternative (no export restrictions) scenario projects an adoption rate 18% above the base-case projection. For herbicide-tolerant cotton, the 70% ceiling

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[5] As an anonymous reviewer observed, "studies of consumer acceptance and knowledge of biotechnology have found that consumers are aware that corn is genetically modified, but generally do not list soybeans as a GM crop." This could be because there have been more "market events" covered by the media (notably the monarch butterfly controversy) related to corn than to soybeans.

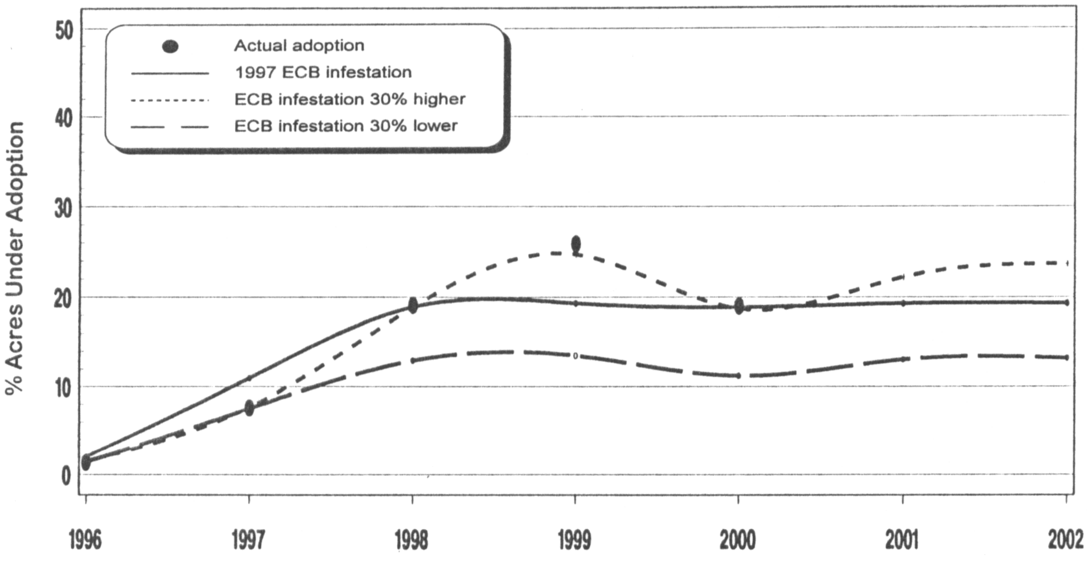

Figure 2. Dynamic diffusion of Bt corn: Adoption limited by ECB infestation levels and refugia requirements, 1996–2002

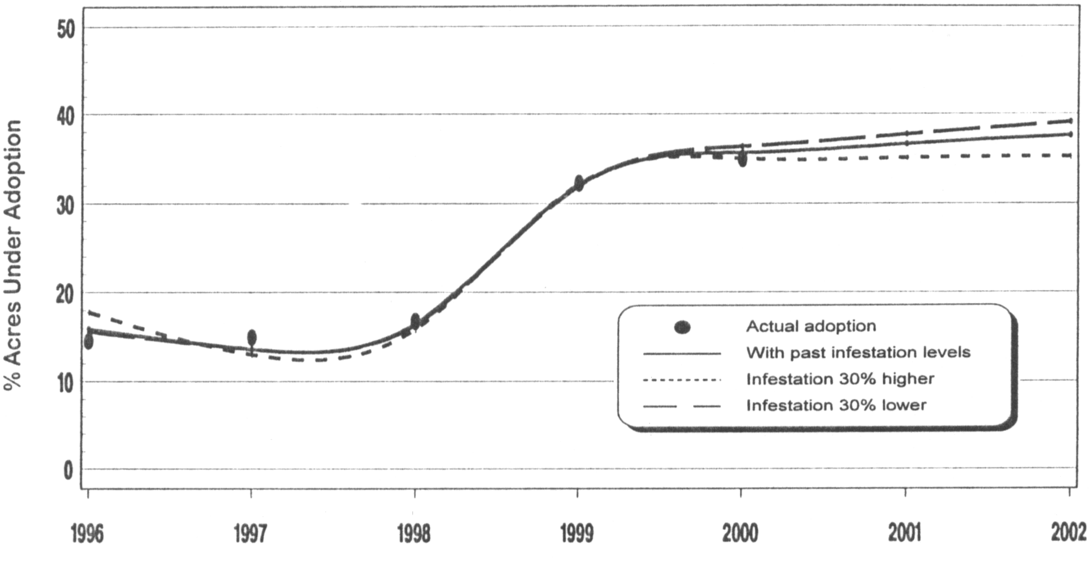

Figure 3. Dynamic diffusion of Bt cotton: Adoption limited by infestation levels and refugia requirements, 1996–2002

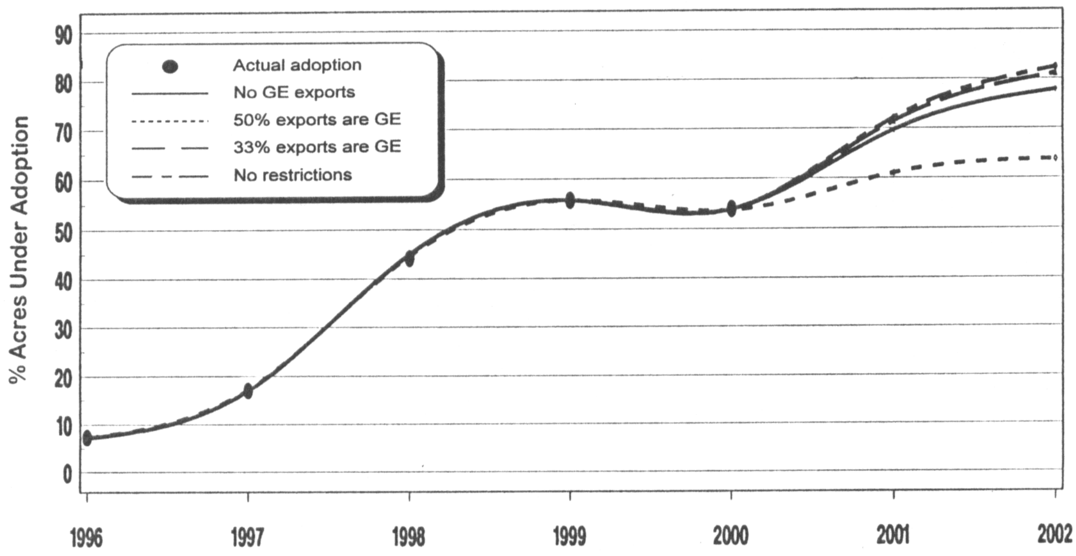

Figure 4. Dynamic diffusion of herbicide-tolerant soybeans with various export assumptions, 1996–2002

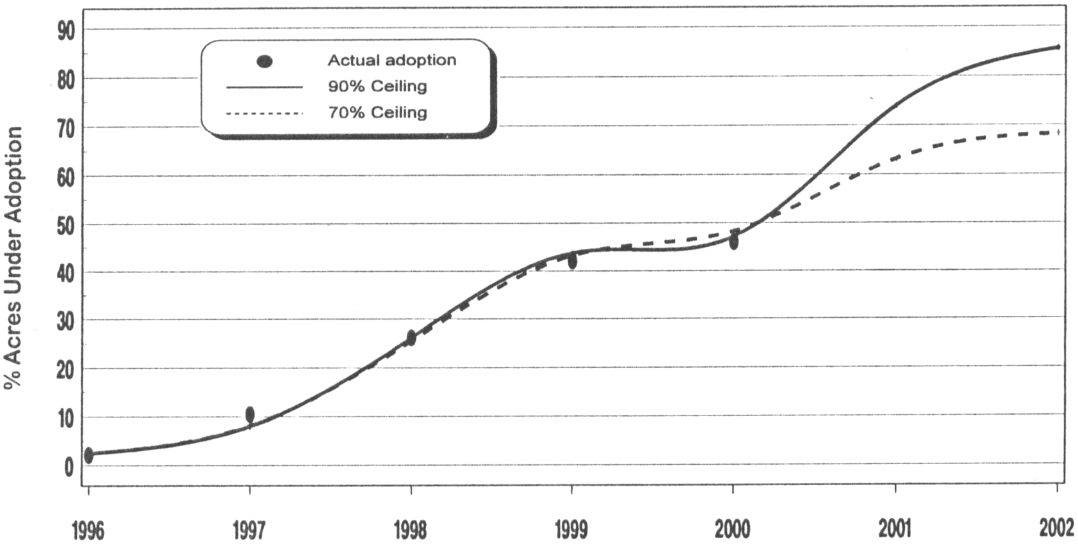

Figure 5. Dynamic diffusion of herbicide-tolerant cotton: Adoption with ceilings of 90% and 70%, 1996–2002

Table 7. Dynamic Logit Diffusion Model Predictions: Bt and Herbicide-Tolerant Crops, 1996–2002 (% of planted acres)

		<!!!!!!!!!!!!!!!!!!!!!!!! SCENARIOS !!!!!!!!!!!!!!!!!!!!!!!!>								
		Past Infestation Levels (base)			Infestation 30% Higher			Infestation 30% Lower		
Year	Actual Adoption	Estimated Adoption	95% Prediction Interval		Estimated Adoption	95% Prediction Interval		Estimated Adoption	95% Prediction Interval	
Bt Corn:										
1996	1.4	2.04	0.43	7.34	1.55	1.04	2.29	1.43	1.08	1.89
1997	7.6	10.94	4.09	16.69	7.64	5.67	9.95	7.52	6.46	8.54
1998	19.1	18.89	17.36	19.22	18.87	16.70	20.63	12.94	12.27	13.25
1999	25.9	19.30	19.21	19.30	24.71	23.12	25.02	13.51	13.42	13.51
2000	19.0	18.86	17.16	19.21	18.69	16.44	20.52	11.22	8.68	12.57
2001	na	19.29	18.77	19.30	22.21	18.83	23.89	13.07	10.88	13.45
2002	na	19.29	19.15	19.30	23.67	22.06	24.45	13.23	11.80	13.47
Bt Cotton:										
1996	14.6	15.96	9.34	24.88	17.81	4.67	33.64	15.68	9.89	23.64
1997	15.0	13.63	8.19	21.17	13.01	3.37	28.96	13.64	8.86	20.24
1998	16.8	16.53	10.06	25.00	15.87	4.32	31.64	16.42	10.71	24.06
1999	32.3	32.05	21.49	41.92	32.21	14.30	39.39	32.00	21.70	43.29
2000	35.0	35.66	25.34	44.54	34.99	18.75	39.97	36.39	26.01	47.01
2001	na	36.64	24.59	46.50	35.09	15.55	40.26	37.74	25.59	49.95
2002	na	37.60	22.97	48.76	35.20	11.25	40.54	39.09	24.29	53.56

		<!!!!!!!!!!!!!!!!!!!!!!!!!!! SCENARIOS !!!!!!!!!!!!!!!!!!!!!!!!!!!>											
		No GE Exports (base)			50% Exports			33% Exports			No Export Restrictions		
Year	Actual Adoption	Est'd Adoption	95% Prediction Interval		Est'd Adoption	95% Prediction Interval		Est'd Adoption	95% Prediction Interval		Est'd Adoption	95% Prediction Interval	
Herbicide-Tolerant Soybeans:													
1996	7.4	6.65	4.27	10.11	6.84	4.65	9.92	6.91	4.83	9.76	6.93	4.89	9.72
1997	17.0	20.00	14.50	26.49	18.40	13.59	24.33	18.21	13.70	23.73	18.15	13.73	23.55
1998	44.2	43.76	36.19	50.16	44.49	35.73	52.99	44.49	35.95	52.99	44.49	36.01	53.01
1999	55.8	55.43	50.06	59.09	55.36	46.14	63.26	55.39	46.09	63.71	55.40	46.05	63.89
2000	54.0	53.75	48.28	57.70	53.92	45.36	61.46	53.92	45.32	61.79	53.92	45.29	61.92
2001	na	60.73	57.69	62.56	69.26	62.49	74.11	71.06	63.77	76.54	71.73	64.24	77.47
2002	na	63.50	61.97	64.27	77.35	73.07	79.87	80.74	75.87	83.76	82.05	76.94	85.28

		<!!!!!!!!!!!!!!!!!!!! SCENARIOS !!!!!!!!!!!!!!!!!!!!>					
		90% Ceiling			70% Ceiling		
Year	Actual Adoption	Estimated Adoption	95% Prediction Interval		Estimated Adoption	95% Prediction Interval	
Herbicide-Tolerant Cotton:							
1996	2.2	2.46	1.34	4.47	2.36	1.09	4.99
1997	10.5	7.97	4.76	13.03	8.10	4.24	14.68
1998	26.2	26.12	15.85	39.50	25.46	14.00	39.65
1999	42.1	43.73	28.75	59.00	43.20	27.84	55.82
2000	46.0	47.12	32.53	61.29	48.30	34.19	58.69
2001	na	74.01	57.07	83.27	63.27	51.00	67.93
2002	na	85.61	72.54	89.03	68.28	59.27	69.76

Note: na = not available at time of estimation.

scenario projects an adoption rate of 15% below the base-case projection.

Based on our analysis, Bt crops will not substantially increase their shares of planted acreage in 2001 or 2002, as shown in figures 2 and 3. Further, since the ceilings are based on past infestation levels of the target pests, adoption may even decline. In contrast, both herbicide-tolerant soybeans and herbicide-tolerant cotton are likely to increase their acreage shares noticeably under all of the scenarios we examine (figures 4 and 5).

These findings suggest that the adoption of herbicide-tolerant crops will continue to increase, unless consumer sentiment in this country changes dramatically. Our forecast is also supported by findings from focus groups regarding Iowa farmers' planting decisions (Alexander, Fernandez-Cornejo, and Goodhue, 2001).

Table 8. Comparison Between Actual Plantings and Out-of-Sample Diffusion Predictions, 2001 (% of acres)

Description	Herbicide-Tolerant Soybeans	Bt Corn	Bt Cotton	Herbicide-Tolerant Cotton
2001 Out-of-Sample Forecast (base case)[a]	61	19	37	74
2001 Actual Plantings[b]	68	19	37	56
Difference (actual minus forecast)	+7	0	0	! 18

[a] Out-of-sample forecast from table 7.
[b] Actual plantings from NASS Acreage Report (USDA, June 29, 2001).

Out-of-Sample Comparison

A "real test" of the model is a comparison of the 2001 out-of-sample forecasts (predictions for 2001 from the diffusion model estimated using only 1996–2000 data) with the results of the actual plantings of GE crops for 2001 which recently became available. To assess an estimated model, one needs to measure its performance. An out-of-sample comparison is more strict and realistic, since in-sample overfitting or data mining improve the model "fit" on historical data but "won't necessarily improve its out-of-sample forecasting performance" (Diebold, 1998, p. 87). As summarized by Wallis (1972, pp. 110–111), "the crucial test of a model is an examination of its predictive performance outside the sample period."

Planting data were collected in a survey conducted by the National Agricultural Statistics Service (NASS) in the first two weeks of June 2001, and the results were published by the USDA in its Acreage Report on June 29 (USDA, 2001). Randomly selected farmers across the United States were asked what they were planting during the current growing season. Questions included whether or not farmers planted corn, soybean, or upland cotton seed that, through biotechnology, is resistant to herbicides, insects, or both. The States, with data published individually in the survey results, represent 82% of all corn planted acres, 90% of all soybean planted acres, and 83% of all upland cotton planted acres.

Except for herbicide-tolerant cotton, the 2001 actual planting data obtained in the USDA survey are very close to the 2001 out-of-sample forecasts obtained from our diffusion model (base cases) (see table 8 and figures 3–6).[6] In the case of herbicide-tolerant cotton, the 2001 actual planting is much lower than the out-of-sample forecast. Thus, the ceiling value used to model the diffusion of herbicide-tolerant cotton may be too high. As discussed earlier, in this case there was not an apparent upper limit on adoption, and therefore we used Rogers' figure of a 90% ceiling. In fact, the actual 2001 planting of herbicide-tolerant cotton is closer to the out-of-sample forecast obtained in the alternative scenario with a 70% ceiling (table 7). This result suggests that while food-safety concerns were not limiting for most consumers of cotton fiber, there may have been some concern related to the use of cotton seed plus some environmental concerns in some sector of the market for cotton fiber which limited the demand of herbicide-tolerant cotton at the margin.

Concluding Comments

This study has examined the diffusion paths of genetically engineered corn, soybeans, and cotton, and forecast the adoption of those crops over the next two years. A dynamic diffusion model was developed, and estimated using a nationwide farm-level survey. In broad terms, the dynamic diffusion models indicate future growth of Bt crops will be slow or even become negative, depending mainly on the infestation levels of Bt target pests. For example, Bt corn adoption rates already appear to be at or above the 1997 estimate of infestation levels. Herbicide-tolerant crops will continue to be grown, particularly cotton, unless there is a radical change in consumer sentiment in this country.

The study has several limitations. Perhaps among the most important is that the data are not entirely consistent; they were obtained from three surveys (one for 1996–98, another for 1999, and the third for 2000) differing in coverage, sample design and size, and phrasing of questions. Moreover, the adoption data for 1996–99 include herbicide-tolerant soybeans

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[6] The results of estimating the diffusion of Bt cotton and herbicide-tolerant cotton technologies together, using the seemingly unrelated regression (SUR) framework, were very similar to the results obtained when estimating each diffusion process separately. Specifically, for the estimated percentage adoption in 2001, the original forecast for Bt cotton = 36.638% and for herbicide-tolerant cotton = 74.014%. The comparable figures for the new forecast (using SUR) are 37.071% and 74.483%, respectively.

obtained using traditional breeding methods (not GE). The 2000 data, on the other hand, excluded these varieties.[7] Also, the ceilings for Bt crops may change with time as the infestation levels change due to exogenous factors, and also endogenously (e.g., the extent of Bt crops planted in a given year is likely to affect the infestation levels of the following years). The overall findings regarding the pattern of adoption for Bt and herbicide-tolerant crops, however, are unlikely to be qualitatively altered by these data limitations.

In addition, it should be stressed that this forecast is only valid for adoption of the technologies currently approved and commercially available. In particular, the diffusion estimates exclude the adoption of rootworm-resistant corn, expected to be available in 2002/3.

The price index of agricultural biotech stocks is a good proxy for market demand conditions for genetically engineered crops. This stock price index does capture relevant agricultural market information and serves as a leading indicator of the acceptance/demand of those biotech products. However, the index is not a very effective proxy for those GE crops where planting decisions are not correlated with events driven by consumer concerns about GE crops.

Finally, the diffusion estimates were calculated before the StarLink incident.[8] While it is likely this contamination problem may have some constricting effect on farmers' future plantings of GE crops, particularly Bt corn, we believe the drop in adoption will not be more drastic than a 30% reduction in ECB infestation levels. [A recent Reuters News Service poll taken during the Farm Bureau Federation annual convention among 400 farmers showed that the StarLink contamination had little impact on U.S. farmers' loyalty to bio-crops, and most U.S. farmers "shrugged off global concerns about genetically modified crops and plan to reduce their 2001 spring plantings only slightly" (Fabi, 2001).]

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[7] Based on a survey conducted through the University of California-Davis, the acreage of herbicide-tolerant soybeans obtained using traditional (non-GE) methods in Iowa was about 2% of the soybean acreage in 1999 (Alexander, Fernandez-Cornejo, and Goodhue, 2000a, 2001). The corresponding U.S. figure is likely to be less. Thus, the measurement error for the case of soybeans in 1999 is likely to be between 1 and 2%.

[8] A news headline reported on September 20, 2000, that some taco shells sold in retail stores contained a protein from StarLink corn, a variety of Bt corn that contained the Cry9C protein, approved by the EPA for feed and industrial uses but not for human consumption (due to a possible question about its potential to cause allergic reactions) (Lin, Price, and Allen, 2001). While StarLink corn was only grown on less than 1% of U.S. corn acreage, the discovery of the protein in some corn foods led to the recall of nearly 300 food products and had repercussions throughout the grain handling chain, processing, as well as in global grain trade (Lin, Price, and Allen).

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