Diffusion of Bioengineered Crops

In order to explore the future adoption of GE crops, this section examines the diffusion paths of genetically engineered corn, soybeans, and cotton and forecasts the adoption of those crops over the next 2 years. Diffusion is the process by which a successful innovation gradually becomes broadly used through adoption by firms or individuals (Jaffe et al., 2000).[4]

Many agricultural innovations follow a well-known diffusion process: after a slow start in which only a few farmers adopt the innovation, the extent of adoption (the fraction of potential users that adopted the innovation) expands at an increasing rate. Eventually, the rate of adoption tapers off as the number of adopters begins to exceed the number of farmers who have not yet adopted. Finally, adoption approaches asymptotically its maximum level, until the process ends. This process generally results in an S-shaped diffusion curve, first discussed by rural sociologists and introduced to economics by Griliches in 1957. Two types of diffusion models—static and dynamic—have been used to examine the progress of agricultural innovations.

Static diffusion models, following the terminology of Knudson (1991), are those growth models that represent the adoption path, expressing the percentage of adopters only as a function of time (they do not contain any other factors). Two characteristics of static models suggest their unsuitability to model some innovations. 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 reaches this maximum.

Unlike static diffusion models, *dynamic diffusion models* allow the coefficients (fixed in static models) that determine the diffusion path to be functions of economic or other factors that affect diffusion. Moreover, dynamic diffusion methods relax some of the assumptions of static diffusion models by allowing for disadoption, and help directly identify and measure the impact of variables significant to the adoption of an innovation.

The diffusion of genetically engineered (GE) crops appears to have followed an S-shaped diffusion curve in 1996-99 (fig. 1), and the static logistic model appears to fit the data. However, the market environment during the past few years, particularly the export market, suggests that use of static diffusion methods may be inappropriate to examine the diffusion of this technology. Increased concern, especially in Europe and Japan, regarding the safety of GE crops has resulted in the development of segregated markets for nonengineered crops. While these markets are still small,[5] the 2000 data regarding the adoption of these crops (fig. 1) suggests that dynamic considerations may be necessary to examine this particular adoption process.

This section examines the diffusion paths of GE crops—including corn, soybeans, and cotton—and discusses possible adoption paths of GE crops through 2002 under different scenarios. Details of the dynamic diffusion model and its estimation using USDA data are presented in Appendix I.

Modeling the Diffusion of GE Crops

The diffusion of GE crops is modeled by specifying a variable-slope logistic function (appendix I). Following Griliches (1957), the variable rate of acceptance (slope) is modeled as largely a demand, or "acceptance," variable. The model is estimated using adoption data obtained from the following USDA surveys (box 1): the ARMS surveys for 1996-98 data, the NASS Crop Production survey for 1999 (USDA, NASS, 1999c), and the NASS Acreage survey for 2000 (USDA, NASS, 2000b). The crops included in the surveys are corn, soybeans, and upland cotton.[6]

Prior to model estimation, it is necessary to specify the ceilings, or maximum adoption levels, of different genetically engineered crops (appendix I). These ceilings are based on limitations due to farm production considerations or market restrictions. That is, for many technologies, not all farmers are expected to adopt the technology. The base-case ceilings for Bt crops are computed by considering infestation levels and refuge

[4] Following Schumpeter (1942), an invention is the first development of a new product or process. If and when an invention is available for commercialization, it becomes a technological innovation.

[5] The market for nonbiotech corn was estimated at about 1 percent in 1999 (Lin et al., 2001) and about 8 percent of Midwest grain elevators were segregating nonbiotech soybeans from commingled soybeans (Shoemaker et al., 2001).

[6] Adoption data for 2001 became available after the completion of this research and were not used in the estimation. This made possible an out-of-sample comparison of 2001 estimates with actual GE plantings obtained from a recent USDA, NASS (2001) survey.

requirements.[7] For example, Bt crops would likely not be adopted on acreage where pest infestation levels do not exceed the economic threshold for treatment. In 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. 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 demand considerations arising in the export market.

Since most cotton acreage is potentially susceptible to weed infestation, a ceiling computed from weed infestation levels is not likely to be binding. In addition, since food safety and consumer concerns in the export market are not likely to be limiting for herbicide-tolerant cotton, there are no apparent *a priori* restrictions in the herbicide-tolerant cotton market. For this reason, we use a ceiling of 90 percent adoption, which is the typical ceiling used for agricultural innovations (Rogers, 1983). A 70-percent ceiling is used to examine the sensitivity of the results to the ceiling specification. In sum, the scenarios analyzed are:

Case	Bt corn/ Bt cotton	Herbicide-tolerant soybeans	Herbicide-tolerant corn
Base	Past pest infestation levels	No GE exports	90-percent ceiling
Alternative	Infestation 30 percent higher	50 percent GE exports	70-percent ceiling
	Infestation 30 percent lower	33 percent GE exports	
		No restrictions	

[7] The Environmental Protection Agency (EPA) requires users of Bt crops to have resistance management plans to ensure that enough susceptible moths survive to mate with resistant ones (Williams, 1997). The insect resistance management (IRM) plans generally require the use of refuge (refugia) areas not planted with Bt varieties where the susceptible moths can survive. For Bt corn, the IRM plan developed by the Agricultural Biotechnology Stewardship Technical Committee (ABSTC) in cooperation with the National Corn Growers Association (NCGA), and accepted by the EPA on January 2000, established a 20-percent refuge requirement in the Corn Belt and 50 percent in the areas of overlapping corn and cotton production (ABSTC, 2001).

Empirical Results

Table 1 summarizes the results of the predicted adoption levels for each crop for the various scenarios considered in each case and includes the 95-percent prediction intervals for each scenario.[8] With the exception of Bt corn in 1999, where adoption was higher than predicted, the actual adoption level was within the 95-percent prediction level for the base scenario for every crop-year observation.

The predicted level of adoption in any period is influenced by the assumption (scenarios) regarding the maximum level of adoption or ceiling. The sensitivity of 2001 and 2002 adoption levels to the specified adoption ceiling varies among technologies and crops. Bt corn is relatively sensitive to the scenario (ceiling) specification. A 30-percent higher corn-borer-infestation scenario projects a Bt corn adoption level (for 2001 corn acreage) 15 percent above the base-case projection; the 30-percent lower infestation projects a level 32 percent below the base-case projection (table 1, fig. 2). In contrast, the comparable numbers for Bt cotton are 4 percent and 3 percent, respectively (table 1, fig. 3). With no export restrictions, the projected adoption rate for herbicide-tolerant soybeans is 18 percent above the base-case projection (no GE exports). For herbicide-tolerant cotton, the 70-percent adoption ceiling scenario projects an adoption rate of 15 percent below the base-case (90-percent ceiling) projection (table 1).

Figures 2-5 show the estimated diffusion paths for each crop and technique under the various scenarios considered. Overall, the estimates suggest that Bt crops will not substantially increase their shares of planted acreage in 2001 or 2002 (figs. 2 and 3). Further, since the ceilings are based on past infestation levels of the target pests, adoption may even decline if infestation levels decrease.

In contrast, the share of both herbicide-tolerant soybeans and herbicide-tolerant cotton increased under all scenarios examined (figs. 4 and 5). This suggests that the adoption of herbicide-tolerant crops will continue to increase, unless U.S. consumer sentiment changes dramatically. This forecast is supported by the findings of focus groups conducted by the University of California, Davis, regarding Iowa farmers' planting decisions (Alexander et al., 2001).

[8] A 95-percent prediction interval implies that there is a 9.5-out-of-10 statistical chance the interval will contain the true value.

Table 1—Dynamic diffusion model predictions - Bt and herbicide-tolerant crops

Percent of planted acres

S C E N A R I O S

Year	Actual adoption	Past infestation levels (base) Estimated adoption	Past infestation levels (base) 95% prediction interval		Infestation 30 % higher Estimated adoption	Infestation 30 % higher 95% Prediction interval		Infestation 30% lower Estimated adoption	Infestation 30% lower 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	15.68	9.89	23.64	17.81	4.67	33.64
1997	15.0	13.63	8.19	21.17	13.64	8.86	20.24	13.01	3.37	28.96
1998	16.8	16.53	10.06	25.00	16.42	10.71	24.06	15.87	4.32	31.64
1999	32.3	32.05	21.49	41.92	32.00	21.70	43.29	32.21	14.30	39.39
2000	35.0	35.66	25.34	44.54	36.39	26.01	47.01	34.99	18.75	39.97
2001	na	36.64	24.59	46.50	37.74	25.59	49.95	35.09	15.55	40.26
2002	na	37.60	22.97	48.76	39.09	24.29	53.56	35.20	11.25	40.54

S C E N A R I O S

Year	Actual adoption	No GE exports (base) Estimated adoption	No GE exports (base) 95% prediction interval		50% exports Estimated adoption	50% exports 95% prediction interval		33% exports Estimated adoption	33% exports 95% prediction interval		No export restrictions Estimated adoption	No export restrictions 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

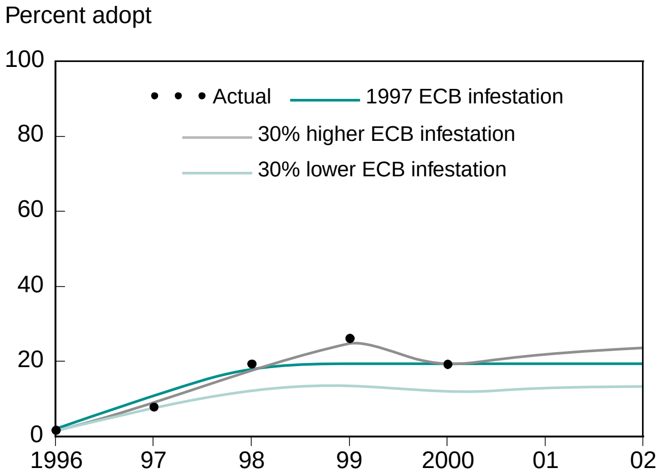
S C E N A R I O S

Year	Actual adoption	90% ceiling Estimated adoption	90% ceiling 95% prediction interval		70% ceiling Estimated adoption	70% ceiling 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

na = Not available at the time of estimation.

Figure 2

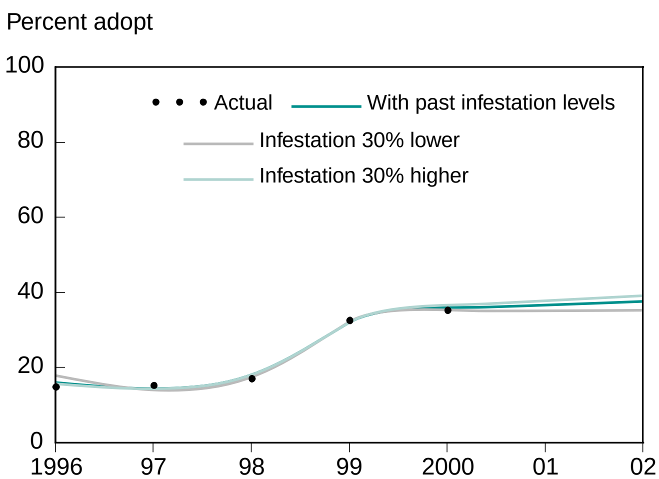
Dynamic diffusion of Bt corn adoption limited by ECB infestation and refugia requirements



Sources: Actual: Fernandez-Cornejo (2000) based on USDA data (Fernandez and McBride, 2000; USDA, NASS, 1999c, 2000b, 2001). Predicted difusion path: Calculated from equation 6 (appendix I).

Figure 3

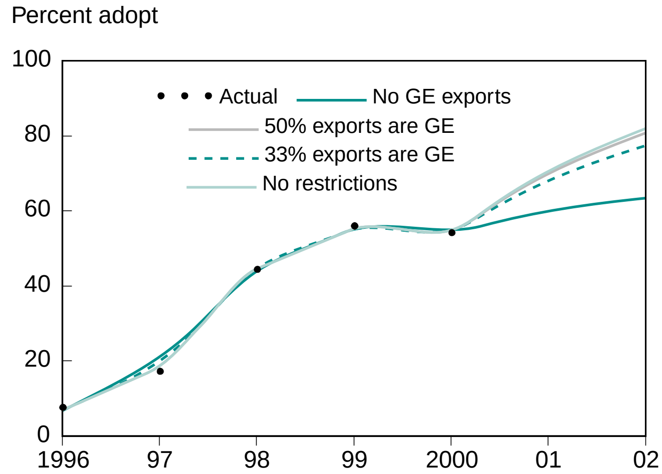
Dynamic diffusion of Bt corn adoption limited by infestation requirements



Sources: Actual: Fernandez-Cornejo (2000) based on USDA data (Fernandez and McBride, 2000; USDA, NASS, 1999c, 2000b, 2001). Predicted difusion path: Calculated from equation 6 (appendix I).

Figure 4

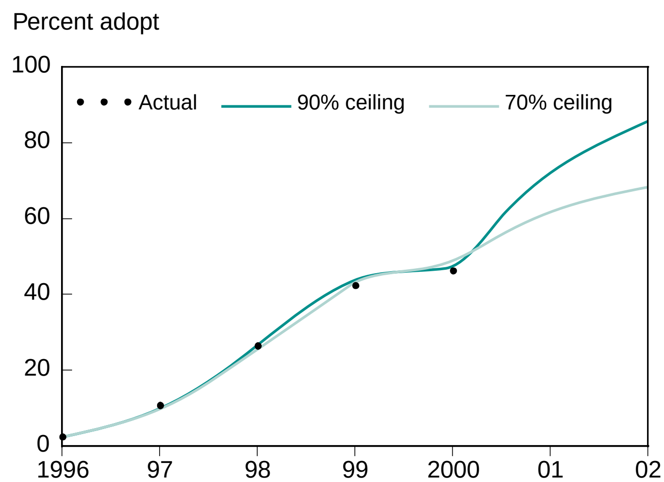
Dynamic diffusion of herbicide-tolerant soybeans with various export assumptions



Sources: Actual: Fernandez-Cornejo (2000) based on USDA data (Fernandez and McBride, 2000; USDA, NASS, 1999c, 2000b, 2001). Predicted difusion path: Calculated from equation 6 (appendix I).

Figure 5

Dynamic diffusion of herbicide-tolerant cotton, ceiling of 90 percent and 70 percent



Sources: Actual: Fernandez-Cornejo (2000) based on USDA data (Fernandez and McBride, 2000; USDA, NASS, 1999c, 2000b, 2001). Predicted difusion path: Calculated from equation 6 (appendix I).

Out-of-Sample Comparison

A "real test" of the model is a comparison of the 2001 diffusion estimates with the results of the actual plantings of GE crops for 2001 that recently became available (these 2001 data were not used in the estimation). As Wallis (1972, pp. 110-111) summarizes it, "the crucial test of a model is an examination of its predictive performance outside the sample period." The sample period used in model estimation is 1996-2000.

The 2001 data were collected in a survey conducted by the National Agricultural Statistics Service (NASS) in the first 2 weeks of June 2001; results were published

Table 2—Comparison between actual plantings and out-of-sample diffusion predictions

	Herbicide-tolerant soybeans	Bt corn	Bt cotton	HT cotton
		Percent of acres		
2001 prediction (base case)[1]	61	19	37	74
2001 actual plantings[2]	68	19	37	56
Difference (actual - prediction)	+7	0	0	-18

[1] From table 1.
[2] From USDA, NASS, 2001.

by USDA in *Acreage* on June 29 (USDA, NASS, 2001). Randomly selected farmers across the United States were asked what they planted during the current growing season. Questions include whether or not farmers planted corn, soybean, or upland cotton seed that, through biotechnology, is resistant to herbicides, insects, or both. The States published individually in the survey results represent 82 percent of all corn planted acres, 90 percent of all soybean planted acres, and 83 percent of all upland cotton planted acres.

Actual 2001 plantings of GE crops (table 2) proved very close to the 2001 predictions from our diffusion model, except for herbicide-tolerant cotton where the 2001 actual plantings are much lower than our predicted value. This suggests that the ceiling used for the diffusion of herbicide-tolerant cotton may be too high (there is no clear adoption ceiling and we used Rogers' 90-percent ceiling, appendix I). In fact, the 2001 actual planting of herbicide-tolerant cotton is closer to the diffusion prediction obtained in the alternative scenario with a 70-percent ceiling (table 1). This suggests that while food safety concerns were not limiting for most consumers of the cotton fiber, some concern related to the use of cotton seed, plus some environmental concerns, may have limited the demand for herbicide-tolerant cotton. In addition, some cotton may have been planted in marginal land in 2001 (as total cotton plantings were the highest since 1995), making it hard to justify the expense on technology fee and seed premiums.

Limitations

The study/model has several limitations. The data are not entirely consistent because they were obtained from various surveys that differ in coverage, sample design and size, and phrasing of questions. Also, the ceilings for Bt crops may change as the infestation levels change due to exogenous and endogenous factors (e.g., the extent of Bt crops planted in a given year is likely to affect the infestation levels of the following years). Moreover, the adoption data for 1996-99 include herbicide-tolerant soybeans obtained using traditional breeding methods (not GE). The 2000 data, on the other hand, exclude these varieties. 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, these estimates are valid only for adoption of technologies currently approved and commercially available. In particular, the estimates exclude the adoption of rootworm-resistant corn, expected to be available in 2003.

Finally, these prediction estimates were made before the StarLink incident.[9] While it is likely that this contamination problem may dampen farmers' future plantings of GE crops, particularly Bt corn, we believe that the drop in adoption will not be more dramatic than with a 30-percent reduction in ECB infestation levels. A recent Reuters poll 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). Actual plantings for 2001 show that Bt corn was grown in 19 percent of corn acres, the same as in 2000, confirming this assessment.

Conclusion

In broad terms, the dynamic diffusion models indicate that 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 level warranted by 1997 infestation estimates. On the other hand, herbicide-tolerant crops will continue to grow, particularly for soybeans and cotton, unless there is a radical change in U.S. consumer sentiment.

[9] 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 possible questions about its potential to cause allergic reactions) (Lin et al., 2001). While StarLink corn was only grown in less than 1 percent 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 as well as in global grain trade (Lin et al., 2001).