Adoption of Bioengineered Crops. By Jorge Fernandez-Cornejo and William D. McBride, with contributions from Hisham El-Osta, Ralph Heimlich, Meredith Soule, Cassandra Klotz-Ingram, Stan Daberkow, Rachael Goodhue, and Corinne Alexander. Agricultural Economic Report No 810.

Abstract

Use of crop biotechnology products, such as genetically engineered (GE) crops with input traits for pest management, has risen dramatically since commercial approval in the mid-1990s. This report addresses several of the economic dimensions regarding farmer adoption of bioengineered crops, including herbicide-tolerant and insect-resistant varieties. In particular, the report examines: (1) the extent of adoption of bioengineered crops, their diffusion path, and expected adoption rates over the next few years; (2) factors affecting the adoption of bioengineered crops; and (3) farm-level impacts of the adoption of bioengineered crops. Data used in the analysis are mostly from USDA surveys.

Keywords: Biotechnology, technology adoption, genetic engineering, pest management, financial effects, tillage, herbicide-tolerant crops, Bt crops, corn, soybeans, cotton.

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1800 M Street, NW
Washington, DC 20036-5831

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Summary

Rapid adoption of new technologies within the U.S. agricultural sector has resulted in sustained increases in agricultural productivity, contributed to economic growth, and ensured an abundance of food. More recently, U.S. farmers are adopting biotechnology innovations that, beyond their impact on productivity, have caused concerns about their potential impact on the environment and opened a Pandora's box of issues surrounding consumer choice, particularly in Europe. These innovations (bioengineered crops) are embedded in the seeds and derive from the use of genetic engineering techniques, which modify organisms by recombinant DNA.

This report summarizes and synthesizes research findings addressing farm-level adoption of genetically engineered (GE) crops. Because there are nonfarm concerns about the technology, an accurate read on benefits and costs to farmers is an important component of a more complete social welfare calculus. Chief among the priorities of this research, given available data, were the following research questions. What is the extent of adoption of first-generation bioengineered crops, their diffusion path, and expected adoption rates over the next few years? What factors have affected the adoption of bioengineered crops and how? And what are the farm-level impacts of the adoption of bioengineered crops available as of the 1990s?

The most widely and rapidly adopted bioengineered crops in the United States are those with herbicide-tolerant traits. These crops were developed to survive the application of specific herbicides that previously would have destroyed the crop along with the targeted weeds, and provide farmers a broader variety of herbicide options for effective weed control. Herbicide-tolerant soybeans became available to farmers in limited quantities in 1996. Use expanded to about 17 percent of the soybean acreage in 1997, 56 percent in 1999, and 68 percent in 2001. Herbicide-tolerant cotton expanded from 10 percent of cotton acreage in 1997 to 42 percent in 1999, and reached 56 percent in 2001. In contrast, the adoption of herbicide-tolerant corn has been much slower and has yet to exceed 10 percent.

Bt crops containing the gene from a soil bacterium, *Bacillus thuringiensis*, are the only insect-resistant GE crops commercially available as of 2002. The bacteria produce a protein that is toxic to certain Lepidopteran insects (insects that go through a caterpillar stage), protecting the plant over its entire life. Bt has been built into several crops, including corn and cotton. After its introduction in 1996, Bt corn grew to 8 percent of U.S. corn acreage in 1997 and 26 percent in 1999, but fell to 19 percent in 2000-01. Bt cotton expanded rapidly from 15 percent of U.S. cotton acreage in 1997 to 32 percent in 1999 and about 37 percent in 2001.

The growth rate of Bt crop adoption will vary over time, both in a positive and a negative direction, mainly as a function of the infestation levels of Bt target pests. The growth rate for Bt corn adoption is likely to be low since adoption has already occurred where Bt protection can do the most good. On the other hand, adoption of herbicide-tolerant crops will likely continue to grow, particularly for cotton, unless there is a radical change in U.S. consumer sentiment. In most cases, the growth of GE crops estimated in this report is validated by the 2001 plantings.

The adoption of herbicide-tolerant soybeans is found to be invariant to farm size, as expected since GE crop technologies only require changes in variable inputs (such as seeds), which are completely divisible. However, the adoption of

herbicide-tolerant and Bt corn is found to be positively related to farm size. For herbicide-tolerant corn, this appears due to its low overall adoption rate, which implies that adopters were largely innovators and other early adopters. As other researchers have observed, adoption is more responsive to farm size at the innovator stage and this effect generally diminishes as diffusion increases. The observed relationship between Bt corn adoption and farm size may have arisen because Bt corn targets a pest problem that is generally most severe in areas where operations growing corn are largest.

GE crop adoption is found to be positively and significantly related to operator education, experience, or both. More educated or experienced operators are more likely to understand that the greatest economic benefits of new technologies accrue to early adopters. The use of contracting (marketing or production) is positively associated with GE crop adoption in most cases, possibly reflecting the greater importance placed on risk management by adopting farms. Contracting also ensures a market for GE crops, reducing price and any market access risk that could result from uncertain consumer acceptance.

Farm-level impacts of GE crop adoption vary by crop and technology. Our estimates are based on 1997 field-level data and 1998 whole-farm data and are obtained from marginal analyses, meaning that the estimated impacts are associated with changes in adoption around the aggregate level of adoption.

The adoption of **herbicide-tolerant corn** improved farm net returns among specialized corn farms (deriving more than 50 percent of the value of production from corn). The limited acreage on which herbicide-tolerant corn has been used is likely acreage with the greatest comparative advantage for this technology. The positive financial impact of adoption may also be due to seed companies setting low premiums for herbicide-tolerant corn relative to conventional varieties in an attempt to expand market share.

The adoption of **herbicide-tolerant soybeans** did not have a significant impact on net farm returns in either 1997 or 1998. Since these findings were obtained from marginal analysis, they imply that an increase from the average adoption rate (45 percent of acreage) in 1998 would not have a significant impact on net returns. However, this is not to say that GE crops have not been profitable for many adopting farms. As a recent study comparing weed control programs found, the use of herbicide-tolerant soybeans was quite profitable for some farms, but the profitability depended specifically on the types of weed pressures faced on the farm and on other factors. This suggests that other factors may be driving adoption for some farms, such as the simplicity and flexibility of herbicide-tolerant soybeans, which allow growers to use one product instead of several herbicides to control a wide range of both broadleaf and grass weeds, and makes harvest “easier and faster.” However, management ease and farmer time savings are not reflected in the standard calculations of “net returns to farming.”

Adoption of **Bt cotton** had a positive impact on net returns among cotton farms but adoption of **Bt corn** had a negative impact on net returns among specialized corn farms. This marginal analysis suggests that Bt corn may have been used on some acreage where the value of protections against the European corn borer (ECB) was lower than the Bt seed premium. Because pest infestations differ across the country (for example, ECB infestations are more frequent and severe in the western Corn Belt), the economic benefits of Bt corn are likely to be greatest where target pest pressures are most severe. Some farmers may also have made poor forecasts of infestation levels, corn prices, and yield losses due to infestations. A reduction in the Bt corn adoption rate between 1999 and 2000-01, from 25 to 19 percent, may be due in part to producers learning where this technology can be used profitably.

On the environmental side, our analysis shows an overall reduction in pesticide use related to the increased adoption of GE crops (Bt cotton; and herbicide-tolerant corn, cotton, and soybeans). The decline in pesticide use was estimated to be 19.1 million acre-treatments, or 6.2 percent of total treatments (1997). Total active ingredients also declined by about 2.5 million pounds. The pounds of active ingredients applied to soybeans increased slightly, as glyphosate was substituted for other synthetic herbicides. However, this substitution displaced other synthetic herbicides that are at least three times as toxic to humans and that persist in the environment nearly twice as long as glyphosate.

Results presented in this report should be interpreted carefully, especially since the impact studies are based on just 2 years of survey data. The extent and impacts of GE crops vary with several factors, most notably annual pest infestations, seed premiums, prices of alternative pest control programs, and any premiums paid for segregated crops. These factors will continue to change over time as technology, marketing strategies for GE versus conventional crops, and consumer perceptions evolve. Finally, the most widely touted farmer benefits of herbicide-tolerant seeds –that it is just plain easy to use and less management intensive—do not get captured by the standard measurement of net returns to management and own labor. Future surveys and analyses will correct for this weakness in our own standard economic yardstick.

Adoption of Bioengineered Crops

Jorge Fernandez-Cornejo and William D. McBride

Introduction

Technological change has been acknowledged as a critical component of productivity and economic growth (Solow, 1994; Griliches, 1995). The rapid adoption and diffusion of new technologies within the U.S. agricultural sector has resulted in sustained agricultural productivity growth and ensured an abundance of food (Huffman and Evenson, 1993; Alston and Pardey, 1996; Ball et al., 1997). However, since technological change can affect employment, trade, real wages, and profits, the adoption of new technologies may trigger asymmetric effects on different sectors of the economy.

International competitiveness and environmental issues have also been linked to technological innovation and adoption (Stoneman, 1995). Furthermore, technology policy issues have surfaced during discussions about the appropriate role of the public sector (e.g., level of public research and development funding) in fostering new innovations and promoting their adoption (Feder and Umali, 1993). Because of the economic opportunities and challenges that new technologies offer, the technology innovation and adoption process continues to interest economists, sociologists, and policymakers.

Economists and sociologists want to understand what causes adoption rates to differ and what constrains the rapid adoption of innovations. Several researchers have examined the influence of farmers' attributes on the adoption of agricultural innovations (Rahm and Huffman, 1984; Caswell and Zilberman, 1985). In the past, most adoption studies focused on technological innovations that increase productivity. Studies have since shifted their focus toward adoption of agricultural technologies that affect environmental quality and conserve scarce natural resources. Thus, during the 1970s and 1980s, studies proliferated on the adoption of environmentally preferable technologies such as IPM (Fernandez-Cornejo, Jans, and Smith; 1998).

More recently, U.S. farmers are adopting biotechnology innovations that, beyond their impact on productivity, have also caused environmental and consumer concerns, particularly in Europe. These innovations (bioengineered crops) are embedded in the seeds and derive from the use of genetic engineering (GE) techniques.

Genetic engineering modifies organisms by recombinant DNA techniques. These techniques allow a more precise and time-saving alteration of a plant's traits, facilitating the development of characteristics that are not feasible through traditional plant breeding. Genetic engineering also allows scientists to target a single plant trait, thus decreasing the number of unintended characteristics that often accompany traditional breeding techniques, and increasing the speed at which breeders can develop new varieties. The first generation of bioengineered crops includes crops with pest management traits, including crops carrying genes (such as the gene from the soil bacterium Bt, *Bacillus thuringiensis)* selected for resistance to certain insects and/or tolerance to specific herbicides.

This report discusses the adoption of GE crops with pest management traits, which has risen dramatically since commercial introduction in the mid-1990s. Issues related to the adoption of these bioengineered crops—including farm impacts, consumer acceptance, environmental safety, and others—are among the leading concerns affecting U.S. agriculture. Because of the controversy surrounding these issues and the continual introduction of new technologies, there is great need for objective measurement and analysis of all components of overall social welfare implications of GE crops—including the farm-level impacts.

Factors Shaping Adoption of Bioengineered Crops

An innovation's profitability, compared with traditional alternatives, has been regarded as the primary motivation behind adoption. This would suggest that the widespread adoption of genetically engineered crops follows from their perceived profitability over traditional methods. However, other factors like producer flexibility, consumer preferences, and farmer attributes and perceptions also influence adoption.

Producer Profitability

The impacts of GE crops on farm profitability vary greatly by region, crop, and technology. Impacts also vary with seed premiums, crop prices, and prices of alternative pest control programs. Moreover, some factors that influence adoption of GE crops are difficult to measure (for example, the economies in management time associated with the adoption of herbicide-tolerant crops). Finally, profits may be affected by factors other than GE adoption, such as other cropping practices, weather, or management ability, making it difficult to isolate the effect of GE crop varieties.

Producers of *herbicide-tolerant crops* versus traditional crops benefit mainly from lower costs. They expect to achieve at least the same output while lowering weed control costs for chemicals, chemical applications, mechanical tillage, and scouting. In return, producers pay more to seed companies for the herbicide-tolerant seed. Thus, the profitability of the herbicide-tolerant program depends on weed control cost savings compared with seed cost premiums. Seed companies aim to set the seed price high enough to obtain as much of the farmers' savings in weed control costs as possible, while still inducing the producer to use the herbicide-tolerant seed. In addition, the substitution of glyphosate, used in most herbicide-tolerant programs, for other herbicides decreases the demand for those herbicides. Thus, the prices of other herbicides decrease, lowering production costs even for those farmers not using the herbicide-tolerant crops.

Other factors believed to affect the economics of adoption of herbicide-tolerant crops are the simplicity and flexibility of the weed control program. Herbicide-tolerant programs allow growers to use one product instead of several herbicides to control a wide range of both broadleaf and grass weeds without sustaining crop injury. Thus, herbicide-tolerant crops appear to free up valuable management time for other activities. However, standard measures of net returns to management (used in this and other studies of this nature) have not been designed to quantify how management intensive a technology is in dollar terms.

Potential users of *Bt crops* (Bt corn or cotton) face a complex decision in determining the relative profitability of these technologies. The use of Bt seed can reduce costs by virtually eliminating the application of insecticides intended to control Bt target pests. More important, because chemical insecticides are not as effective as the control achieved with Bt seed, planting Bt seed increases crop yields, as crop losses are reduced. Therefore, Bt crops are more profitable than traditional insect control measures only if the target pest infestations are severe enough to cause economic losses greater than the economic impact of the price premium paid for the Bt seed. However, unlike annual weed infestations that are relatively stable and predictable, insect infestations can vary dramatically each year (Gray and Steffey, 1999). Since the decision to plant Bt crops must be made prior to observing the insect infestation, the farmer may or may not make the most economical decision for a given year depending upon the resulting infestation. Thus, Bt crops act as insurance against significant losses that may occur in the event of severe pest infestations.

Consumer Preferences

Consumers express their preferences for bioengineered crops at the market and producers must respond to the economic signals that these preferences convey. Factors influencing consumer preferences include (1) their perceptions of benefits and risks of bioengineered crops on human health and the environment, (2) their ethical stance toward genetic engineering, and (3) their trust in government regulations concerning risk assessment and management (OECD, 2000). The importance of these factors has varied substantially among consumers both within and among countries, causing significant uncertainty about the acceptance of bioengineered crops, particularly in international markets. This uncertainty may discourage adoption of these crops, particularly food crops.[1] In addition, specific markets for nonbiotech crops have emerged as consumers have expressed their preferences.

Environment

While many of the environmental benefits and risks of GE crop adoption are dificult to quantify, changes in pesticide use associated with the adoption of GE crops are surely an important effect of GE crops (Royal

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[1] Cotton is a particular case. While food safety concerns may not be limiting for most consumers of the cotton fiber, there may be some concern related to the use of cotton seed. In addition, there may be environmental concerns in some sector of the market for cotton fiber that limits the demand for herbicide-tolerant cotton at the margin.

Society, 1998; Henry A. Wallace Center, 2000). Several recent polls among consumers indicate that consumers were willing to accept biotechnology as a means of reducing chemical pesticides used in food production (Farm Bureau/Philip Morris Gap Research, 2000). More specifically, consumers would be likely to buy a variety of produce "if it had been modified by biotechnology to be protected from insect damage and required fewer pesticide applications" (IFIC Foundation, 2001).

Other Factors

While profitability (i.e., the extent of yield increases and/or input cost reduction versus the costs of adoption relative to the current management practices) is key to explaining the extent and rate of technology adoption, most studies acknowledge that heterogeneity among farms and farm operators can often explain why all farmers may not adopt an innovation in the short or long run (Khanna and Zilberman, 1997; Batte and Johnson, 1993; Lowenberg-DeBoer and Swinton, 1997). Differences influencing readiness to adopt include farm size, tenure, operator education/experience, and access to information and credit. The nature of the technology or the financial, locational, and physical attributes of the farm may also influence profitability and, ultimately, the adoption decision.

Other factors that may have some effect on adoption include the interaction of GE crops with other cropping practices. For example, the adoption of herbicide-tolerant crops complements the conservation tillage practices and narrow row spacing. Adoption may also have some impact on the safety of farmworkers and other people operating (or living) in nearby areas. For example, as the use of Bt crops ensures that insect control is properly timed and reduces the need to handle and apply synthetic insecticides, it thereby increases farmworker safety and avoids the misapplication or drift of chemicals from the target area (Rice and Pilcher, 1998).

Objectives and Roadmap

USDA's Economic Research Service (ERS) has studied bioengineered crops and their adoption by farmers since 1998. The farm-level component of this research program addresses the following three questions. What is the extent of adoption of bioengineered crops, their diffusion path, and expected adoption rates over the next few years? What factors have affected the adoption of bioengineered crops and how? Finally, what are the farm-level impacts of the adoption of bioengineered crops? The GE crops considered in this report include those with herbicide-tolerant and insect-resistant traits—the principal GE crops available to and adopted by U.S. farmers.

Data to address these questions came mostly from surveys conducted by USDA. This report summarizes and synthesizes the findings from several research projects addressing farm-level adoption of GE crops. The appendices include details about some of the projects.

The first section of this report summarizes the extent of adoption of bioengineered crops, including herbicide-tolerant soybeans, corn, and cotton; and Bt corn and cotton. The next section examines the diffusion process of bioengineered crops, and discusses possible adoption paths of these crops through 2002, under different scenarios. Following that, we examine the factors that influence the adoption of GE crops by focusing on adoption in corn and soybean production (i.e., herbicide-tolerant corn and soybeans and Bt corn). In addition, we measure the influence of various factors on the adoption decision, with special emphasis on farm size.

The last, and perhaps most difficult, question is examined in the last two sections. The microeconomic effects of adoption are examined first. In particular, has adoption of GE crop varieties affected the economic performance of U.S. farm businesses and, if so, how has the impact varied across farms? To answer this question, the impacts of adoption on corn, soybean, and cotton producers are evaluated using 2 years of data.

The final section explores the potential impacts from adoption of GE crops on the environment occurring via changes in pesticide use and in tillage practices. A complete analysis of environmental benefits and risks of GE crop adoption is beyond the scope of this report, as data to quantify a range of factors are not available. Still, examining the changes in pesticide use associated with the adoption of GE crops is important in assessing the effects of GE crops (Royal Society, 1998; Henry A. Wallace Center, 2000).

The Extent of Adoption of Bioengineered Crops

Herbicide-Tolerant Crops

The mostly widely adopted bioengineered crops have been those with herbicide-tolerant traits. These crops were developed to survive the application of specific herbicides that previously would have destroyed the crop along with the targeted weeds, and provide farmers a broader variety of herbicide options for effective weed control. The most common herbicide-tolerant crops are 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 corn that is resistant to glufosinate-ammonium, and cotton that is resistant to bromoxynil.[2]

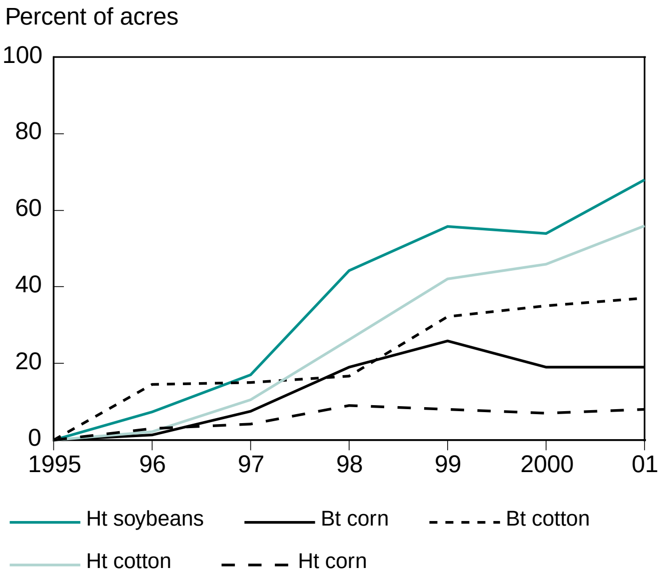
The adoption of most herbicide-tolerant crops has been particularly rapid. Herbicide-tolerant soybeans became available to farmers for the first time in limited quantities in 1996. Use expanded to about 17 percent of the soybean acreage in 1997, to 56 percent in 1999, and to 68 percent in 2001 (fig. 1). Herbicide-tolerant cotton expanded from 10 percent of cotton surveyed acreage in 1997, to 42 percent in 1999, and to 56 percent in 2001.[3] To contrast, the adoption of herbicide-tolerant corn has been much slower, reaching a plateau at 8-9 percent of corn acreage in 1998-2001 (see box 1 for a description of the data used to obtain the adoption estimates).

Insect-Resistant Crops

Crops inserted with insect-resistant traits have also been widely adopted. Bt crops containing the gene from a soil bacterium, *Bacillus thuringiensis*, are the only insect-resistant crops commercially available. The bacteria produce a protein that is toxic when ingested by certain Lepidopteran insects (insects that go through a caterpillar stage). The Bt technology is a novel approach to controlling insects because the insecticide is produced throughout the plant over its entire life. Therefore, the insecticide is more effective than conventional and biological insecticides because it cannot be washed off by rain or broken down by other environmental factors. Bt has been built into several crops, including corn and cotton.

Figure 1

Adoption of GE crops in the United States



Source: Fernandez-Cornejo (2000) based on USDA data (Fernandez and McBride, 2000; USDA 1999b, 2000b, 2001).

Bt corn provides protection mainly from the European corn borer. The Environmental Protection Agency (EPA) approved Bt corn in August 1995, and its use grew to about 8 percent of the corn acreage in 1997 and to about 26 percent in 1999, before receding to 19 percent in 2000-01 (fig. 1). Bt cotton is primarily effective in controlling the tobacco budworm, the bollworm, and the pink bollworm. Use of Bt cotton expanded to 15 percent of cotton acreage in 1997, to 32 percent in 1999, and to 37 percent in 2001.

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[2] In addition to GE crops, there are traditionally bred herbicide-tolerant crops, such as corn resistant to imidazolinone (IMI) and sethoxydim (SR), and soybeans resistant to sulfonylurea (STS).

[3] For the case of corn and cotton, acres of crops with stacked traits (containing both Bt and herbicide-tolerant traits) are counted as acres in each category.

Box 1—USDA Survey Data

The USDA surveys that provided agricultural production data—including the adoption of genetically engineered (GE) corn, cotton, and soybeans used in this report—are the Agricultural Resource Management Study (ARMS) surveys (data used for 1996-98), the Objective Yield Survey (results used for 1999), and the June Agricultural Survey (results used for 2000).

1996-98 Data - TheNASS/ERS ARMS Surveys. The Agricultural Resource Management Study (ARMS) surveys developed by the Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS) of USDA are conducted each year starting from 1996. The ARMS survey is designed to link data on the resources used in agricultural production to data on use of technologies (including the use of genetically engineered crops), other management techniques, chemical use, yields, and farm financial/economic conditions for selected field crops. Each survey included three phases (screening, obtaining production practices and cost data, and obtaining financial information). As shown in the accompanying table, the number of (major) States covered by the surveys varies by crop and year, but each survey includes States that account for between 79 and 96 percent of U.S. acreage in the specified crop.

The ARMS is a multi-frame, probability-based survey in which sample farms are randomly selected from groups of farms stratified by attributes such as economic size, type of production, and land use. Each selected farm represents a known number of farms with similar attributes. Weighting the data for each surveyed farm by the number of farms it represents is the basis for calculating estimates for all U.S. farms.

The adoption data results for 1998-99 from ARMS have been summarized and reported (Fernandez-Cornejo and McBride, 2000) using the new set of farm resource regions depicting geographic specialization in production of U.S. farm commodities recently constructed by ERS (USDA, ERS, 1999). The eight farm-resource regions recognize both new capabilities and standards in the resolution of relevant data, and overcome some longstanding problems with the older USDA Farm Production Regions. In constructing the farm resource regions, ERS analysts identified where areas with similar types of farms intersected with areas of similar physiographic, soil, and climatic traits, as reflected in USDA's Land Resource Regions. A U.S. map depicting the regions is shown in the figure below.

1999 Data - The NASS Objective Yield Survey. The 1999 adoption data are based on responses from the seed variety questions on the 1999 objective yield and farm operator survey conducted between September and October to gather information on expected yields. The information was published in the report titled *Crop Production* (USDA, NASS, 1999c). The objective yield surveys (OYS) for corn, soybeans, and cotton were conducted in the major producing States that account for between 61 and 71 percent of the U.S. production (see accompanying table). NASS conducts objective yield surveys in major corn, soybean, and upland cotton producing States each year (USDA, NASS, 1999c). Randomly selected plots in corn for grain, soybean, and upland cotton fields are visited monthly from August through harvest to obtain specific counts and measurements. The farm operator survey was conducted primarily by telephone with some use of mail and personal interviewers. Approximately 15,000 producers were interviewed during the survey period and surveyed throughout the growing season to provide indications of average yields as the season progresses.

Detailed information concerning the selected fields is obtained during an initial producer interview. Respondents were asked if they planted seed that was resistant to herbicides or insects. Herbicide-tolerant varieties include those developed using both biotechnology or conventional breeding techniques. Insect-resistant varieties include those containing Bt. These data are intended to show trends in production practices but not official estimates of the Agricultural Statistics Board.

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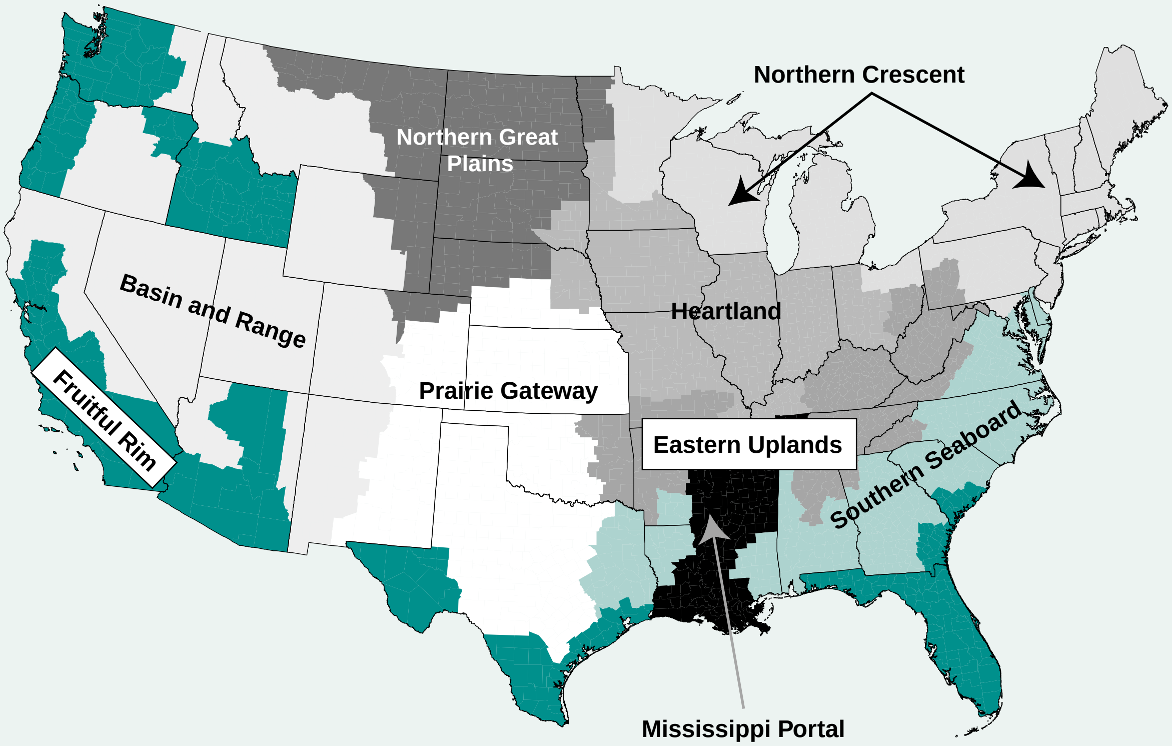
ERS Resource Regions



USDA survey coverage in percent of area planted (number of States in parentheses)

	ARMS[1]			OYS[2]		Acreage[3]
	1996	1997	1998	1998	1999	2000
Corn	88(16)[4]	77(10)[5]	89(16)[6]	61(7)[7]	62(7)[7]	100(All)[8]
Cotton	83(8)9	96(12)[10]	92(10)[11]	63(5)[12]	63(5)[12]	100(All)[8]
Soybeans	79(12)[13]	93(19)[14]	91(16)[15]	71(8)[16]	71(8)[16]	100(All)[8]

[1] ARMS: Agricultural Resource Management Study carried out by the USDA.

[2] OYS: Objective Yield Survey carried out by the USDA; percentages refer to area harvested.

[3] June Agricultural Survey published in the *Acreage* report (USDA, NASS, 2000b).

[4] IL, IN, IA, KS, KY, MI, MN, MO, NE, NC, OH, PA, SC, SD, TX, WI (reported in USDA, NASS/ERS, 1997).

[5] IL, IN, IA, MI, MN, MO, NE, OH, SD, WI (reported in USDA, NASS/ERS, 1998).

[6] CO, IL, IN, IA, KS, KY, MI, MN, MO, NE, NC, OH, PA, SD, TX, WI (reported in USDA, NASS/ERS, 1999).

[7] IL, IN, IA, MN, NE, OH, WI (reported in USDA, NASS, 1999c).

[8] All States included in the estimating program for the crop (reported in USDA, NASS, 2000b).

[9] AZ, AR, CA, GA, LA, MS, TN, TX (reported in USDA, NASS/ERS, 1997).

[10] AL, AZ, AR, CA, GA, LA, MS, MO, NC, SC, TN, TX (reported in USDA, NASS/ERS, 1998).

[11] AL, AZ, AR, CA, GA, LA, MS, NC,TN, TX (reported in USDA, NASS/ERS, 1999).

[12] AR, CA, LA, MS, TX (reported in USDA, NASS, 1999c).

[13] AR, IL, IN, IA, LA, MN, MS, MO, NE, OH, TN, WI (reported in USDA, NASS/ERS, 1997).

[14] AR, DE, IL, IN, IA, KS, KY, LA, MI, MN, MS, MO, NE, NC, OH, PA, SD, TN, WI (reported in USDA, NASS/ERS, 1998).

[15] AR, IL, IN, IA, KS, KY, LA, MI, MN, MS, MO, NE, NC, OH, SD, TN (reported in USDA, NASS/ERS, 1999).

[16] AR, IL, IN, IA, MN, MO, NE, OH (reported in USDA, NASS, 1999c).

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2000 Data - The NASS June Agricultural Survey. The 2000 adoption data were collected as part of the June Agricultural Survey that NASS conducted the first 2 weeks of June and published on June 30, 2000, in the report titled *Acreage* (USDA, NASS, 2000b). These surveys are based on a probability area farm survey with a sample of about 10,800 segments or parcels of land (averaging approximately 1 square mile) and a probability sample of more than 77,700 farm operators. Enumerators conducting the area survey contact all farmers having operations within the sampled segments of land and account for their operations. Farmers in the list survey sample are contacted by mail, telephone, or personal interview to obtain information on their operations. Responses from the list sample, plus data from operations that were not on the list to be sampled, are combined to provide another estimate of planted and harvested acres (USDA, NASS, 2000b).

Regarding GE crops, during the first 2 weeks of June 2000, randomly selected farmers across the United States were asked if they planted seed that, through biotechnology, was resistant to herbicides, insects, or both (USDA, NASS, 2000b). Unlike previous surveys, herbicide-tolerant varieties in this survey include only those developed using biotechnology. Conventionally bred herbicide-tolerant varieties were excluded from the survey. Insect-resistant varieties include only those containing Bt. Stacked gene varieties include those containing GE traits for both herbicide and insect resistance.

Comparability Among Surveys. Data from the different USDA surveys are not directly comparable because of inconsistencies that arose because none of the surveys were specifically designed to collect data on genetically engineered varieties. Rather, questions on adoption of GE crops were added to different USDA survey instruments the main objective of which was other than measuring the extent of adoption of these crops. As a consequence, survey coverage among surveys is often different. There are also some differences in the base acreage used to calculate the percentage of adoption, and the questions related to GE adoption are not identical in different surveys.

Coverage. As shown in the preceding table, coverage varies among the different surveys and crops. The Objective Yield Survey (OYS) appears to have the lowest coverage (61 percent of the acreage for corn in 1998) and the 2000 acreage survey the highest. The ARMS survey reached about 90 percent of the acreage for each of the three crops in 1998. Since NASS provided adoption information at State level for 2000, it is possible to calculate the ratio of the U.S. adoption rate of GE crops relative to the rate for States covered by the OYS. For 2000, these ratios are highest for Bt cotton (1.31) and herbicide-tolerant cotton (1.18). This means that a direct comparison of adoption rates using, for example, OYS data for 1999 and acreage survey data for 2000 may be misleading.

Acres planted. Unlike all other sources, which reported the adoption rates relative to planted acres, the objective yield survey reported the adoption rates relative to harvested acres. Since the ratio of planted to harvested acres ranges from 1.02 for soybeans to 1.25 for upland cotton (in 1998), a comparison of data reported with a different base may also be misleading.

Questions. The questions in the different surveys were not identical. An extreme example is the case of herbicide-tolerant crops. Adoption data for 1996-99 include herbicide-tolerant corn and soybeans obtained using traditional breeding methods (not GE) such as STS soybeans. The 2000 data, on the other hand, excluded these varieties. While adoption of these non-GE soybean varieties is known to be small (between 2 and 3 percent for the case of soybeans in Iowa), we do not know the precise amounts nationwide. Thus, no attempt was made to estimate this effect.

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

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[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	

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).

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[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).

[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

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	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

SCENARIOS

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

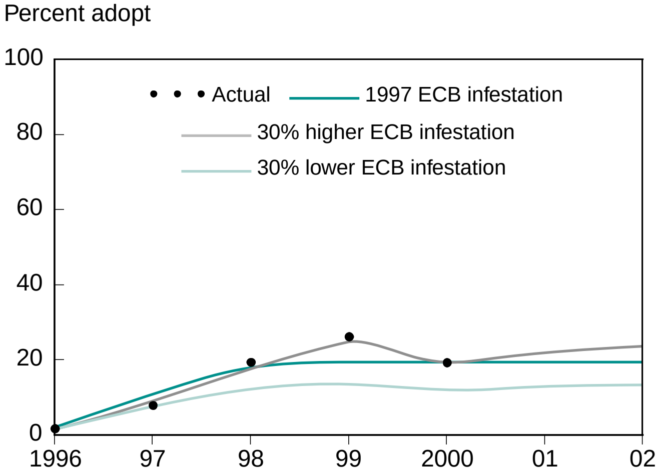
SCENARIOS

		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

na = Not available at the time of estimation.

Figure 2

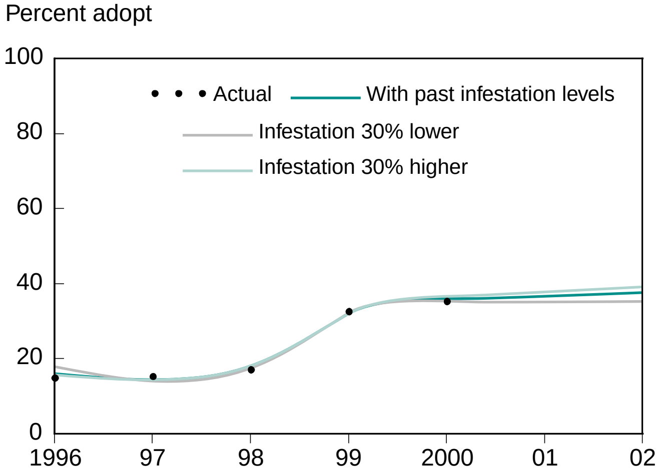
Dynamic diffusion of Bt corn adoption limited by ECB infestation and refugia requirements



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

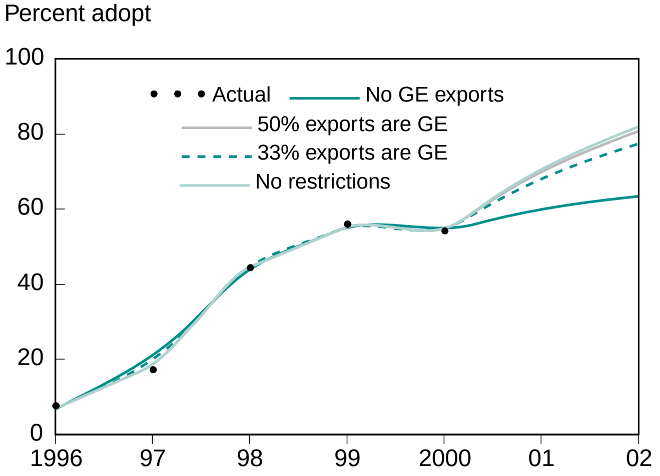
Dynamic diffusion of Bt corn adoption limited by infestation requirements



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

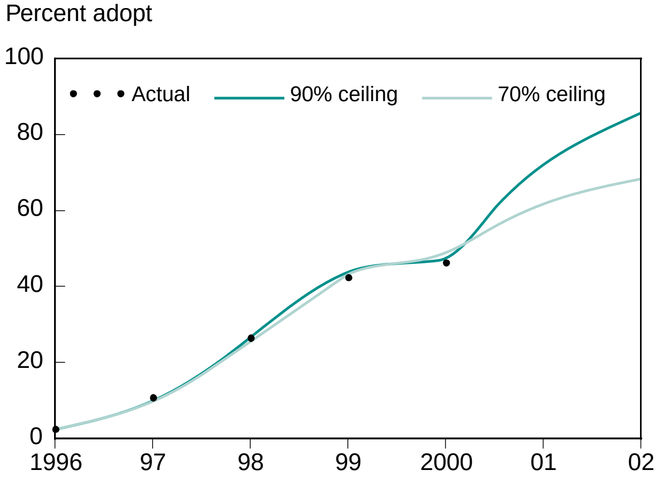
Dynamic diffusion of herbicide-tolerant soybeans with various export assumptions



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.

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[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).

Factors Affecting the Adoption of Bioengineered Crops

Since technological change can affect the level of output, product quality, employment, trade, real wages and profits, the adoption of new technologies offers economic opportunities and challenges. Consequently, understanding the adoption process continues to be of interest to economists, sociologists, and policymakers (box 2). Of particular interest to policymakers is the impact of new technologies on farm structure (i.e., farm size), and the role that farm structure plays in the adoption process.

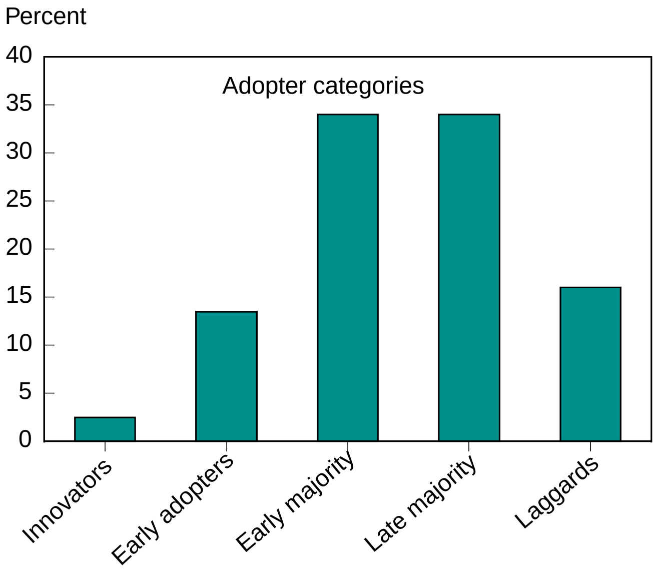
Numerous technology adoption studies have been conducted over the last 40 years, beginning with Griliches (1957) and Rogers (1961) (see box 2). Feder, Just, and Zilberman (1985) and Feder and Umali (1993) review many of these studies. Of note, Rogers (1961, 1995) hypothesized that innovators or early adopters (fig. 6) have attributes different from later adopters or nonadopters. Feder and Umali (1993) distinguish between adoption factors during the early phases of adoption versus the final stages of adoption; factors such as farm size, tenure, education, information, and credit may be significant for the early adopters but not for later adopters.

A few empirical analyses of the factors affecting GE crop adoption of have appeared thus far. Fernandez-Cornejo and McBride (2000) report that larger operations and more educated operators are more likely to use herbicide-tolerant soybeans. They also report that higher crop prices are more likely to raise adoption, while conventional tillage is likely to reduce adoption (farmers use conventional tillage to help control weeds, whereas herbicides are typically used with conservation or no-till practices). Alexander, Fernandez-Cornejo, and Goodhue (2000b) examine the role of risk aversion in producer behavior for corn and soybean producers, finding that risk preferences, as measured by responses to survey questions, are likely to influence the decision to plant GE corn but not soybeans.

The objectives of this section are to: (1) examine the factors that influence the adoption of GE crops by focusing on adoption in corn and soybean production (i.e., herbicide-tolerant corn and soybeans and Bt corn), and (2) contrast the relative influence of various factors on the adoption decision for these technologies, with special emphasis on the role of farm size.

Figure 6

Rogers' characterization of adopters



Source: Adapted from Rogers (1983, p. 247).

Modeling Crop Adoption

The factors that influence adoption of genetically engineered crops are examined empirically using econometric techniques, specifically a Tobit model, presented in Appendix II. This model allows the estimation of the likelihood of adoption as well as the extent (i.e., intensity) of adoption. The Tobit model is preferable to binary adoption models when the decision to adopt also involves simultaneously a choice regarding the intensity of adoption (Feder and Umali, 1993), as it does with GE crops.

Results of the Tobit analysis for the adoption of genetically engineered crops are presented in detail in Appendix II, including the estimated coefficients, standard errors, and calculated marginal effects. The marginal effects are used to calculate the elasticities of adoption with respect to each of the significant explanatory variables (table 3). An elasticity of adoption measures the responsiveness of adoption to a particular factor, and is equal to the relative change in adoption of a technology with respect to a small relative change in a given factor (for example, farm size) from current levels. The elasticities obtained from the Tobit model take into account that a change in an explanatory variable will simultaneously affect the number of adopters and the proportion of acreage under adoption. For example, an elasticity of adoption with respect to size equal to 0.26 means that a 10-percent increase from the mean size (harvested acres) leads to an increase in the expected

Box 2—Previous Research on the Factors Affecting Agricultural Technology Adoption

Economists and sociologists have made extensive contributions to the literature on the adoption and diffusion of technological innovations in agriculture (e.g., Feder et al., 1985; Rogers, 1995). Such research typically focuses on the long-term rate of adoption and the factors that influence the adoption decision

The characteristics (perceived or real) of a new innovation are widely known to influence the adoption decision (Rogers, 1995; Batz et al., 1999). Rogers (1995) hypothesized that five technology attributes affect the rate of adoption: relative advantage (i.e., profitability, initial cost, status, time savings, and immediacy of payoff over conventional practice); compatibility (i.e., similarity with previously adopted innovations); complexity (degree of difficulty in understanding and use); trialability (i.e., ease of experimentation); and observability (i.e., degree to which the results of the innovation are visible). Using this characterization, GE crops have several unique attributes that would be expected to impact its adoption rate, including: low initial or fixed cost; high degree of compatibility (i.e., with current weed control practices), low degree of complexity, trialability (i.e., divisible), and observability.

Farm Structure/Size. A basic hypothesis regarding technology transfer is that the adoption of an innovation will tend to take place earlier on larger farms than on smaller farms. Just, Zilberman, and Rausser (1980) note that given the uncertainty, and the fixed transaction and information costs associated with innovations, there may be a critical lower limit on farm size that prevents smaller farms from adopting. As these costs increase, the critical size also increases. It follows that innovations with large fixed transaction and/or information costs are less likely to be adopted by smaller farms. However, Feder et al. (1985) point out that lumpiness of technology can be somewhat offset by the emergence of a service sector (i.e., custom service or consultant) that can essentially turn a nondivisible technology into a divisible one.

Disentangling farm size from other factors hypothesized to influence technology adoption has been problematic. For example, Feder et al. (1985) caution that farm size may be a surrogate for other factors, such as wealth, risk preferences, and access to credit, scarce inputs, or information. Moreover, access to credit is related to farm size and land tenure because both factors determine the potential collateral available to obtain credit. Also, farm size is affected positively by the amount and quality of management labor and, since farm size can be varied in the short run by renting, farm size is also affected by profitability and credit considerations (Gould et al., 1989). And El-Osta and Morehart (1999) point out that the higher tolerance toward risk (which is a function of greater wealth and a more diversified portfolio) and the greater human capital of operators of large farms may also explain why large farms have incentives or propensities to adopt new technology. Among rural sociologists, Rogers (1995) points out that, empirically, adopter category characteristics and farm size appear interrelated.

Human Capital. The ability to adapt new technologies for use on the farm clearly influences the adoption decision. Most adoption studies attempt to measure this trait through operator age, formal education, or years of farming experience (Fernandez-Cornejo et al., 1994). More years of education and/or experience is often hypothesized to increase the probability of adoption whereas increasing age reduces the probability. Factors inherent in the aging process or the lowered likelihood of payoff from a shortened planning horizon over which expected benefits can accrue would be deterrents of adoption (Barry et al., 1995; Batte and Johnson, 1993). Younger farmers tend to have more education and are often hypothesized to be more willing to innovate.

Risk and Risk Preferences. In agriculture, the notion that technological innovations are perceived to be more risky than traditional practices has received considerable support in the literature. Many researchers argue that the perception of increased risk inhibits adoption (Feder et al., 1985). When an innovation first appears, potential users are generally uncertain of its effectiveness and tend to view its use as experimental (Mansfield, 1966). Hiebert (1974) and Feder and O’Mara (1981, 1982) show that uncertainty declines with learning and experience, thus inducing more risk-averse farmers to adopt an innovation provided it is profitable. Innovators and other early adopters are believed to be more inclined to take risks than are the majority of farmers.

continued on page 15

Continued from page 14

While risk attitudes are often hypothesized to influence technology adoption, the use of specific risk management tools may also be associated with the adoption decision. Market and production risks faced by most producers can be managed via a variety of mechanisms, including contracting, integration, adjusting input and/or output levels, storage, hedging, diversifying, time sequencing transactions, and insurance (Robison and Barry, 1987). Contracting, while very common in fruit and vegetable production, is increasing among growers of specialty corn and soybeans, especially with the introduction of GE crops where producers need to be assured of a market (Bender and Hill, 2000; Perry et al., 1977). King (1992) points out that for processors, contracts "...help ensure predictable supplies and quality. For producers, they can offer price stability and access to specialized expertise, information and inputs (p. 1217)."

The role of risk aversion in producer behavior in the adoption of GE crops is examined by Alexander, Fernandez-Cornejo, and Goodhue (2000). They find that among corn and soybean producers, those who reduce their acreage in one GE crop are more likely to reduce their acreage in the other GE crop, indicating that producer risk preferences are independent of the crop. They also find that risk preferences, as measured by responses to survey questions, are positively and significantly related to the decision to plant GE corn. This suggests that risk and returns both support a reduction in GE corn acreage. In contrast, risk preferences do not explain the share of GE soybeans, which is consistent with the prediction that the production characteristics of GM soybeans dominate the price uncertainty. These results are consistent with risk-averse or risk-neutral producers.

Tenure. Land ownership is widely believed to encourage adoption of technologies linked to land. While several empirical studies support this hypothesis, the results are not unanimous and the subject has been widely debated (e.g., Feder et al., 1985). For example, Bultena and Hoiberg (1983) find no support for the hypothesis that land tenure had a significant influence on adoption of conservation tillage. The apparent inconsistencies in the empirical results are due to the nature of the innovation. Land ownership is likely to influence adoption if the innovation requires investments tied to the land. Presumably, tenants are less likely to adopt these types of innovations because they perceive that the benefits of adoption will not necessarily accrue to them. Because the use of bioengineered crops does not require land-tied investments, land tenure may not affect adoption of this technology.

Labor Supply. Given the high level of interdependency between the household and farm business, the combined labor supply of the operator and spouse indicates the total amount of time available for farming and nonfarming activities. Operator and/or spouse off-farm employment may constrain adoption of management-intensive technologies because it competes for farm managerial time (McNamara et al., 1991). Conversely, adoption by households with off-farm employment may be encouraged if the technology is operator labor-saving, as may be the case with GE crops.

Credit Constraints. Any fixed investment requires the use of own or borrowed capital. Hence, the adoption of a nondivisible technology, which requires a large initial investment, may be hampered by lack of borrowing capacity (El-Osta and Morehart, 1999). GE crops clearly do not fit the model of a capital-intensive technology. Consequently, a credit or capital constraint should not have an adverse impact on the adoption of GE crops.

Location Factors. Location factors—such as soil fertility, pest infestations, climate, and availability or access to information—can influence the profitability of different technologies across different farms. Heterogeneity of the resource base has been shown to influence technology adoption and profitability (Green et al., 1996; Thrikawala et al., 1999). Also, the source of vendors for technologies may vary spatially, as well as the perceived need for the technology. Dummy variables that represent location or resource variables such as region, soil type, weather, climate, availability of information, etc., are often used to control for spatial variation in adoption.

proportion of corn acres planted with Bt corn by 2.6 percent. The interpretation of the elasticity for binary variables, such as operator education, is somewhat different. For example, a 10-percent increase in the *proportion* of corn farmers pursuing education beyond high school would lead to an increase of 3.4 percent in the expected proportion of corn acres planted with herbicide-tolerant corn.

Our analysis of the factors affecting GE adoption focuses on the role of farm size. Since the adoption literature suggests that farm size is often a surrogate for other factors (e.g., wealth, access to credit—see box 2), this study attempts to control for many of these factors in order to isolate the effect of farm size on adoption.

Effect of Farm Size

Characteristics of GE crop technologies led us to expect that adoption would be invariant to farm size. GE crop technologies are embodied in the variable inputs (e.g., seeds), which are completely divisible. Thus, GE crops may be used in any amounts, unlike technologies embodied in "lumpy" inputs like tractors or other machinery, which require extensive capital investments and many acres over which the operator can spread the costs of acquisition.[10]

However, actual mean adoption rates for different farm sizes, obtained directly from 1998 USDA survey data, are not constant (fig. 7). Adoption rates appear to increase with size of operation for all the technologies, but in different patterns. For example, the adoption of herbicide-tolerant soybeans and corn was fairly stable (39-52 percent for soybeans and 6-10 percent for corn) for farms above 50 acres. In contrast, the adoption of Bt corn increased continuously with the size of the operation.

Table 3—Factors affecting the adoption of GE crops, 1998

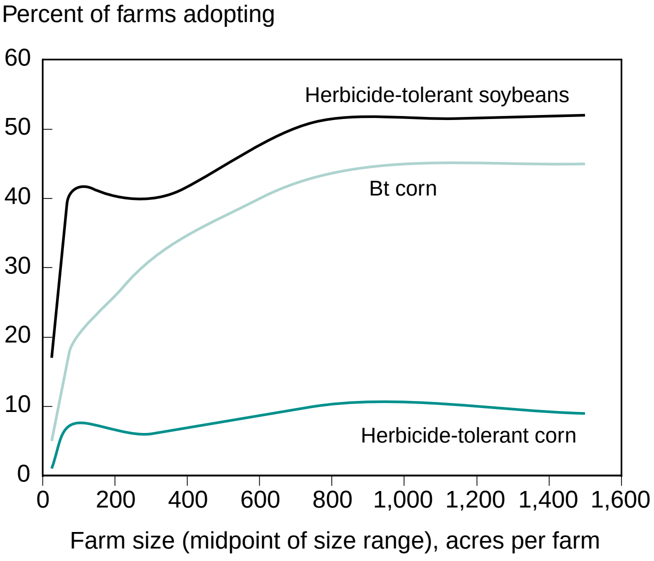
Factor	Herbicide-tolerant soybeans	Bt corn	Herbicide-tolerant corn
		Elasticity[1]	
Education	0	0.179	0.336
Experience	0.236	0	0.453
Marginal region	-0.079	0	0
Size	0	0.258	0.279
Risk	-0.859	0	0
Limited-resource	-0.049	0	0
Contract	0.036	0.022	0
High infestation	na	0.123	na

[1] The contribution of each factor toward adoption is measured as an elasticity. The elasticity of adoption is the relative change in (the probability of) adoption relative to a small relative change in the contributing factor. An elasticity of zero indicates a statistically insignificant underlying coefficient.

na = Not applicable

Figure 7

Adoption of GE corn and soybeans (sample averages) by size of operation, 1998



Source: ARMS data.

While illustrative, this comparison of means would be valid only in an ideal experimental setting where factors other than size are "controlled" by making them as similar as possible. Thus, differences in mean adoption rates cannot necessarily be attributed to size since survey results are influenced by many other

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[10] We have avoided a discussion of the dependency of technology adoption on scale because of its technical nature and the controversy involved in its discussion. Researchers have debated whether certain technologies are scale dependent (e.g., "exhibit economies at large scales") and therefore are more likely to be adopted by larger farms (Kuchler and Offutt, 1986). The static definition of a scale-neutral technology requires that it involves an inexpensive variable-cost input, whereas a scale-biased technology "involves a fixed cost input and requires large capital investment" (p. 86) (El-Osta and Morehart, 1999). A dynamic approach is offered by Kinnucan et al. (1990), who maintain that scale dependency is determined by the pattern of adoption not by whether the cost is variable or fixed. By this definition, if early adopters "do happen to operate large farms, [the] new technology de facto is biased in favor of the large farmer, regardless of input type." Kinnucan et al. further argue that the crucial question is whether larger farmers have "natural propensities to adopt early." For them, early adoption is related to the ability of larger farm operations to assume risks and acquire information. Risk behavior and ability to process information depend, in turn, on management attitudes, skills, and experience, which may ultimately determine the decision to adopt early.

factors not controlled for, including location, access to credit, risk, wealth, other cropping practices, etc.

For these reasons, we proceed directly to the econometric results, which support the prior hypothesis of invariance to size for the adoption of herbicide-tolerant soybeans, after controlling for other factors (table 3). However, the adoption of herbicide-tolerant corn and Bt corn are positively related to farm size.[11] The different empirical results obtained for the adoption of herbicide-tolerant soybeans (invariance to farm size) and herbicide-tolerant corn (adoption positively related to farm size) from the Tobit analysis may be understood by examining their adoption rates. The 1998 adoption rate for herbicide-tolerant soybeans in the sample (34 percent of farms) implies that adoption of herbicide-tolerant soybeans has progressed past innovator and early adopter stages (fig. 6) into the realm where adopting farmers are much like the majority of farmers. On the other hand, the adoption of herbicide-tolerant corn was quite low in 1998 (5 percent of farms), implying that adoption of this technique was largely confined to innovators and other early adopters who tend to control substantial resources and are willing to take the risks.

This result is consistent with Rogers' observation that adoption is more responsive to farm size at the innovator stage and that the effect of farm size on adoption generally diminishes as diffusion increases.[12] This effect can be more closely examined by using the decomposition of the responsiveness (measured by the elasticity) of adoption with respect to size into components that reflect the behavior of users and nonusers of the technology. The decomposition of the elasticity of size for each technology (table 4) reveals that adoption of herbicide-tolerant corn by nonusers was much more responsive to changes in size than for the other technologies (0.442 percent per 1-percent increase in size).[13]

The results for Bt corn are more difficult to interpret. Bt corn was adopted by 20 percent of farms in 1998, a level inclusive of more than innovators and other early adopters (Rogers, 1995). However, unlike herbicide-tolerant soybeans, the estimated adoption elasticity of Bt corn with respect to size was positive and significant. One important difference between Bt corn and the herbicide-tolerant technologies is that Bt corn is designed to target a pest with much more spatial variation than pests targeted by the other technologies. European corn borer (ECB) infestations are quite severe in some areas and virtually nonexistent in others. Although we attempted to control for spatial variability in ECB infestations, it may be that the measured impact of farm size on Bt corn adoption was influenced by the correlation between farm size and ECB infestations. In fact, many western corn-producing States (e.g. Iowa, Nebraska) tend to have large corn farms and are also more likely to have high ECB infestations. It would have been interesting to examine if Bt corn adoption increases with size among farms with an ECB infestation above a certain threshold, but this analysis could not be conducted because of insufficient data.

Moreover, the responsiveness of the adoption to farm size was largest for the farms that had already adopted Bt corn in some of their corn acreage (in those farms, an

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[11] The analysis also shows that for Bt corn, both the linear and quadratic coefficients of the size terms are significant, the linear term positive and the quadratic term negative. This implies that in this case, there is a maximum size beyond which adoption no longer increases with increased size. The maximum, at which adoption declines as size increases, occurs at a size of 1,170 acres (which is about a fifth of the largest corn farm in the sample). The maximum does not exist for herbicide-tolerant corn because only the linear term is significant, or for herbicide-tolerant soybeans because they are invariant to size.

[12] Rogers (1995) observes that empirically, adopter category characteristics and farm size appear interrelated. He posits the following generalizations with respect to innovators and early adopters compared with other adopter categories: they are more educated; have higher social status as measured by such variables as income and wealth; have larger farms; tend to be commercial farms rather than subsistence or part-time farms; are more likely to understand and use credit; are likely to have greater association with change agents (i.e., media, consultants, extension, etc.); and have more specialized farming operations. Rogers (1995) reasons that innovators and early adopters (fig. 6): (1) need to control considerable resources to absorb possible losses from an unprofitable innovation, (2) have an ability to understand and apply complex technical language, and (3) have an ability to cope with uncertainty associated with any new innovation.

[13] According to the extension of the McDonald-Moffit decomposition for a two-limit Tobit (appendix II), three components of the elasticity can be identified. The first component indicates how responsive the probability of adoption is to changes in size. For Bt corn, with a 1-percent increase in average size, the probability of adopting Bt corn by nonusers would increase by 0.217 percent. The second component indicates how responsive the proportion of acreage under adoption by current users of the technology is to changes in size. As average size increases by 1 percent, the proportion of acres with Bt corn would increase by 0.483 percent for current adopters. The last elasticity component, unique to the two-limit Tobit, indicates how responsive the probability of having all acreage under the technology is to changes in size. If size increases by 1 percent, the probability of using Bt on all corn acreage increases by 0.74 percent.

Table 4—The size effect on adoption

Item	Herbicide-tolerant soybeans	Bt corn	Herbicide-tolerant corn
Elasticity of size (measured at the means):			
Total elasticity of adoption with respect to size-- Increase in percent of acreage under adoption for all farmers per a 1-percent increase in size	0	0.258	0.279
Decomposition of the elasticity of size			
Increase in the probability of adoption by non-adopters (in percent) per a 1-percent increase in size	0	0.217	0.442
Increase in percent of acreage under adoption for farmers that have already adopted per a 1-percent increase in size	0	0.483	0.242
Probability (in percent) of having all planted acres under adoption per a 1-percent increase in size	0	0.074	0.104
Size			
Size at which the elasticity of adoption becomes negative, 1,000 acres	na	1.170	Infinity
Largest farm in the sample, 1,000 acres	7.00	5.89	5.89

Note: An elasticity of zero indicates a statistically insignificant underlying coefficient. na = Not available.

increase in size of 1 percent led to an increase in the Bt corn acreage of 0.483 percent, table 4). Adopters of Bt corn may choose to plant Bt corn throughout the operation because ECB infestations tend to be widespread. Thus, once the decision to control for ECB is made, it is implemented across much of the operation. However, the probability that a given farm would have all their acreage under adoption was lower for Bt corn than herbicide-tolerant adopters because of refuge requirements associated with Bt corn.

To conclude, the interrelationships between the attributes of innovations and the characteristics of adopters at different stages of the diffusion process make it difficult to examine the influence of size on the adoption of innovations. Theoretically, this difficulty is inherent to the data commonly available and could be surmounted if the model included every factor that characterizes an innovator such that size effect could be totally isolated. In practice, one uses proxies for most relevant factors, such as risk, operator management skills, etc., which are limited by the quality of the data. It is doubtful that adoption patterns can be used to categorize technologies as size invariant or size dependent because such categorization depends not only on the attributes of the innovation but also on the extent of adoption and characteristics of the adopters.

Moreover, technology adoption is a dynamic process. This study attempted to measure the role of farm size in adoption at one point in time (1998) and does provide a point of reference. Comparing these results with measurements at future points in the diffusion process would further the understanding of how the characteristics of these technologies influence their adoption by farms of various sizes.

Effect of Other Factors

Adoption of all three of the GE crop technologies was positively and significantly influenced by operator's education, experience, or both (table 3). These factors may also reflect management quality in the sense that more educated or experienced operators are more likely to understand that the economic benefits of new technologies usually accrue to early adopters.[14]

The use of contracting (marketing or production) was positively associated with technology adoption in most of the models. The effect of contracting may be indicative of the greater importance placed on risk manage-

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[14] However, operator experience was not significantly associated with the adoption of Bt corn. Experience implies a better understanding of the pressures exerted by pests and the economic threshold for adoption, particularly important in the decision whether to adopt Bt corn. Thus, while operator experience may have been crucial for the adoption decision, experience had no significant association with the decision **to adopt** because experienced operators adopt (or not) if the expected benefits of adoption exceed expected costs (or not).

ment by adopting farms. Contracting locks in a commodity price or service fee and ensures a market for GE crops, lessening price and any market access risk that could result from uncertain consumer acceptance of these crops. GE crops also reduce production risks by lowering the likelihood of yield losses due to weed and insect pressure.

Location of the operation outside of the primary production area (outside the Heartland and the Mississippi Portal, appendix 2) was associated with a lower expected adoption for herbicide-tolerant soybeans. Among the farm typology variables (developed by ERS and defined in detail by Hoppe et al., 1999, 2000), only the limited-resource classification variable[15] was significant in the model for herbicide-tolerant soybeans, and these farms were less likely to adopt (as expected, given their more limited access to information and capital necessary to afford the GE technology fees). Corn borer infestation had a significant and positive influence on the expected adoption of Bt corn. Credit reserves, off-farm work, and land tenure were not significant in any of the adoption models. Compared with other agricultural innovations, such as soil conservation improvements, these factors are probably less important to the adoption of GE crops because of their unique attributes, such as low fixed costs.

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[15] Limited-resource farms are small farm operations with annual sales less than $100,000, assets less than $150,000, and household income less than $20,000.

Microeconomic Impact of Adopting Bioengineered Crops

Faced with reduced returns to crop production caused by low commodity prices, farmers are examining alternative technologies as ways to improve financial performance by cutting costs and/or increasing yields. Rapid adoption of GE crop varieties among farmers suggests that these technologies are perceived to have advantages over traditional methods. GE crop varieties with pest management traits provide a broad spectrum of potential benefits and appeal to farmers because they promise to simplify pest management, reduce its costs, increase its effectiveness, and increase flexibility in field operations. But impacts vary by crop and technology and are often confounded with other factors, making it difficult to isolate the effect of adopting GE crop varieties on yield and profits. For example, the physical environment of the farm (e.g., weather, soil type) affects profitability directly through increased fertility and indirectly through its influence on pests.

This section examines the economic impact of GE crop adoption on U.S. farms. Has the adoption of GE crop varieties affected the economic performance of U.S. farm businesses? If so, how has the impact varied across farms? To accomplish this objective, the impacts of adoption on corn, soybean, and cotton producers are evaluated using both 1997 field-level and 1998 whole-farm survey data.[16] Field-level data provide more accurate information regarding yields and input uses; whole-farm data allows the calculation of broader measures of farm financial performance. In both cases, the analyses shown in this report can be considered as a marginal analysis, meaning that the estimated financial impacts are associated with changes in adoption around the aggregate level of adoption.

Econometric Models

Field-Level Analysis

The field-level analysis used the econometric model developed by Fernandez-Cornejo, Klotz-Ingram, and Jans (1999) to estimate the impact of adopting GE crops on yields and net returns using 1997 field-level survey data. The model takes into consideration that farmers' adoption and pesticide use decisions may be simultaneous (Burrows, 1983). In addition, the model corrects for self-selection.[17] Finally, the model is consistent with farmers' desire to maximize profits (Fernandez-Cornejo, Klotz-Ingram, and Jans, 1999; Fernandez-Cornejo and McBride, 2000).

The field-level analyses include herbicide-tolerant soybeans, herbicide-tolerant cotton, and Bt cotton. Each technology was modeled individually using 1997 survey data. Each model included pest infestation levels, other pest management practices, crop rotations, and tillage. Geographic location was included as a proxy for soil, climate, and other local factors that might influence the impacts of adoption. Net returns (in this context also called gross margin and variable profits) are defined as per-acre revenues minus per-acre variable expenses, including pesticides, seed (including technical fee), and labor.

Results of such modeling are expressed as elasticities. In our context, an elasticity is the relative change in a particular measure (e.g., yields, profits) relative to a small relative change in adoption of the technology from current levels. The results can be viewed in terms of aggregate impacts across the entire agricultural sector as more producers adopt the technology, or in terms of a typical farm as they use the technology on more of their land. As with most cases in economics, the elasticities estimated in the quantitative model should only be used to examine small changes (say, less than 10 percent) away from current levels of adoption.

Whole-Farm Analysis

The whole-farm analysis assesses the impact of adopting GE crops on farm financial performance using the econometric model shown in appendix III. The model uses 1998 farm-level survey data described in box 1 (pp. 5-7). By controlling for several other factors that may also affect financial performance—such as economic and environmental conditions, management practices, and operator characteristics—

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[16] Corn and soybeans are leading users of agricultural pesticides at a substantial cost to U.S. farmers. These two crops comprised about 70 percent of the herbicide poundage, and more than 20 percent of the insecticide poundage used on major U.S. field crops in 1995 (Fernandez-Cornejo and Jans, 1999). Average chemical costs for corn, at $28 per acre, are nearly 20 percent of operating costs. Chemical costs average about $25 per acre for soybeans, comprising about a third of total operating costs (USDA, ERS, 2000a).

[17] Self-selection arises because farmers are not assigned randomly to the two groups (adopters and nonadopters), but make the adoption choices themselves. Therefore, adopters and nonadopters may be systematically different and these differences may manifest themselves in farm performance and could be confounded with differences due purely to adoption (Greene, 1997).

the model attempts to isolate the effect of GE crop adoption on farm financial performance.

Separate models were estimated for herbicide-tolerant corn, Bt corn, and herbicide-tolerant soybeans. The models were specified using variables that have shown to be related to technology choice in previous research (box 2, pp. 14-15). Several measures of farm financial performance were examined, but results are reported for only two measures: net returns per tillable acre and modified net farm income per tillable acre.[18]

Net returns were measured as gross value of crop production minus total farm chemical and seed expenses, where gross value of crop production is the production of each crop commodity produced on the farm operation valued at the State-average price received by farmers (USDA, NASS, 1999a). This measure of financial performance was used because most of the financial impacts of adopting GE crops result from changed crop yields, reduced chemical costs, and increased seed costs. Thus, this measure captures the greatest influence that GE crop adoption would have on whole-farm financial performance as it filters out the impact that other farm activities —such as livestock production, custom work, and government program participation— have on financial performance. Moreover, this measure is consistent with the "net returns" variable used in the field-level analysis as well as other studies on the relative economies of GE and conventional crops (box 3).

Modified net farm income was measured as net farm income (NFI) plus interest expense. NFI was calculated as gross farm income minus total farm operating expenses (excluding marketing expenses). The measure of net farm income used in this analysis measures the return to operator and unpaid family labor, management, and capital (both equity and borrowed). Interest expenses are added back to net farm income so that variation in farm debt does not influence the financial comparison among farms. Because of the influence of several factors on MNFI, the impact of GE crop adoption would need to be relatively strong in order to have a significant effect on MNFI.

The whole-farm analysis of the impact of adopting GE corn (soybeans) was conducted on two segments of the farm population: (1) operations that harvested one or more acres of corn (or soybeans), and (2) operations that specialized in the production of corn (or soybeans), with more than 50 percent of the total value of farm production from corn (soybeans). Such specialized farms were examined in addition to all growers because GE technologies likely have the greatest financial impact on operations specializing in the target commodities.

The whole-farm analysis also examined the effect of spatial variation on the impact of GE crop adoption using the ERS farm resource regions (box 1). Because pest infestations differ across the country, one would expect the impacts of pest control measures such as GE crops to be greatest where target pest pressures are most severe. Research suggests that the value of Bt corn relative to conventional varieties increases as one moves from east to west in the Corn Belt, because ECB infestations are much more frequent and severe in the western Corn Belt (Hyde et al., 2000). Also, weed pressure tends to be greatest in the eastern and southern United States because of the hot, moist climate and the longer growing season. Therefore, the expected returns of herbicide-tolerant crops would be greater in these areas because of higher costs for conventional weed control.[19]

Empirical Results

Field-Level Results

GE crops available for commercial use do not increase the yield potential of a variety. In fact, yield may even decrease if the varieties used to carry the herbicide-tolerant or insect-resistant genes are not the highest-yielding cultivars. However, by protecting the plant from certain pests, GE crops can prevent yield losses compared with non-GE varieties, particularly when infestation of susceptible pests occurs. This effect is particularly important in Bt crops. For example, before the commercial introduction of Bt corn in 1996, the European corn borer (ECB) was only partially

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[18] Other financial performance measures examined in this study were an estimate of operator labor and management income (net farm income less charges for unpaid labor and capital) per tillable acre and rate of return to assets. These results were very similar to those obtained for the net farm income measure.

[19] The farm resource regions are used to reflect agro-climatic variation across the country and the differences in pest pressures this creates. One change to the regional delineation is that the Heartland is divided along the Mississippi River into the East Heartland and the West Heartland. This change better reflects the difference in weed and ECB pressure between these areas.

Box 3—Previous Research on the Economic Impact of GE Crop Adoption

Published research about the economic benefits from using herbicide-tolerant crops has been mixed. Data from field trials in West Tennessee were used in an economic analysis of Roundup Ready soybeans (Roberts, Pendergrass, and Hayes, 1999). Comparing per acre net returns from 14 trials, the returns from the Roundup system were 13 percent higher than the returns for the second most profitable system. Higher returns from the Roundup system resulted from both higher yields and lower herbicide costs. Research results from experimental trials in Mississippi (Arnold, Shaw, and Medlin, 1998) also showed higher yields and net returns from Roundup Ready soybeans versus conventional varieties. Other partial budgeting results also showed higher returns from Roundup Ready versus conventional weed control for soybeans (Marra, Carlson, and Hubbell, 1998; Reddy and Whiting, 1999). However, research using experimental data on Roundup Ready and conventional corn varieties in Kentucky did not show a significant difference in returns above seed, herbicide, and fixed costs (Ferrell, Witt, and Slack, 1999).

While economic analyses based on experimental data have mostly favored herbicide-tolerant crops over conventional varieties, results from producer surveys have not been as definitive. Research using data from 1997 and 1998 cost of production surveys in Mississippi suggested that pesticide costs were lower with Roundup Ready soybeans, but lower pesticide costs were offset by the added technology fee (Couvillion et al., 2000). McBride and Brooks (2000) compared mean seed and pest control costs estimated from a 1997 national survey of soybean producers. Results of the comparison did not indicate a cost advantage, or disadvantage, for herbicide-tolerant versus other soybean varieties. Using the same data, Fernandez-Cornejo, Klotz-Ingram, and Jans (1999) developed an econometric model to estimate the impact of adoption on net returns after other factors, including cropping practices, agronomic conditions, and producer characteristics, were statistically controlled. Results of this study also did not show a significant change in net returns to soybean production from the adoption of herbicide-tolerant soybeans. Similar results were obtained in an analysis of the impacts from adopting herbicide-tolerant corn (Fernandez-Cornejo and Klotz-Ingram, 1998).

Published research about the economic benefits from using Bt corn suggests that the value of Bt corn relative to traditional varieties depends primarily upon the yield loss that can be attributed to damage from the ECB. Results from field trials controlling the level of ECB infestation indicated that at the highest ECB injury level, Bt corn hybrids yielded more than 10 bushels per acre more than conventional varieties (Graeber, Nafziger, and Mies, 1999). The authors concluded that at $2.25 per bushel corn, and $12 per acre for the Bt technology, it takes about 5 bushels per acre more yield to pay for the ECB protection. Similar results were reported by Rice and Pilcher (1998) who showed how returns to Bt corn vary with the expected corn yield, the number of corn borers per plant, and the effectiveness of pest control. Because the economic benefits from Bt corn are tied to the level of ECB infestation, studies in some areas have found that the value of protection from Bt corn is not likely to exceed its cost. Hyde et al. (1999) found that the value of protection offered by Bt corn under Indiana conditions is generally lower than the premium paid for Bt seed corn. Similarly, research under Wisconsin conditions suggests that Bt seed may not be worth the additional cost because of a low probability of infestation (Lauer and Wedberg, 1999). Research by Hyde et al. (2000) suggests that the value of Bt corn relative to conventional varieties increases as one moves from east to west in the Corn Belt because ECB infestations are much more frequent and severe in the western Corn Belt.

controlled using chemical insecticides. The economics of chemical use were not always favorable and timely application was difficult, so farmers often accepted yield losses (of 3 to 6 percent per one corn borer per plant depending on the stage of plant development) rather than incur the expense.

From this perspective, for the cases analyzed, the empirical results are not surprising. Adoption of herbicide-tolerant soybeans led to a small but statistically significant increase in yield while adoption of Bt cotton led to a large increase in yields (table 5). A 10-percent increase in the adoption of herbicide-tolerant soybeans led to a 0.3-percent increase in yields (elasticity of yields is +0.03).[20] On the other hand, an increase of 10 percent in the adoption of adoption of Bt cotton in the Southeast increased yields by 2.1 percent (elasticity is +0.21).[21]

The adoption of herbicide-tolerant cotton also has a positive and statistically significant effect on net returns (elasticity is +0.18), as does the adoption of Bt cotton (elasticity of +0.22). However, the adoption of herbicide-tolerant soybeans does not have a statistically significant effect on net returns (table 5). As discussed in more detail in a later section, the soybean results appear to be inconsistent with the rapid adoption of this technology. Yet, other factors have a considerable impact on adoption, namely the simplicity and flexibility of the weed control program, which frees up valuable management time for other activities. However, it is difficult to measure management involvement on various technologies from survey data.

Whole-Farm Results

GE crop adoption was found to affect net returns on specialized corn farms. Adoption of herbicide-tolerant corn had a positive and statistically significant effect on net returns, but the elasticity of net returns with respect to adoption was negative for Bt corn (table 5). The effect of GE crop adoption on farm financial performance was not significant for soybean farms.

An analysis using broader financial performance measures (including net farm income and return on assets) did not show GE crops to have a significant impact. GE crop technologies do not require a capital investment and, thus, their impact on farm finances is mainly limited to changes in variable costs and returns. For this reason, adoption-impact models are likely to be more useful in explaining net returns than in explaining farm income.[22]

The impact of GE crops on the net returns of specialized corn farms varied by region (table 6). On all specialized corn farms nationwide, a 10-percent increase in herbicide-tolerant corn led a 2.7-percent rise in net returns. But in the eastern Heartland, the increase in net returns expanded to 4.1 percent, consistent with high weed pressures there. In contrast, the adoption of Bt corn led to a decrease in net returns among specialized corn farms; as adoption increased

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[20] Adoption of herbicide-tolerant cotton also led to significant yield increase in 1997 (elasticity of +0.17).

[21] The analysis of Bt cotton focused on the Southeast region because States there show much higher rates of adoption of Bt cotton than other regions (Falck-Zepeda and Traxler, 1998) and infestation levels of pests nontargeted by Bt appear to be more important than Bt target pests in the rest of the cotton-producing States.

[22] Previous studies have had much more success in explaining the variation in net farm income (El-Osta and Johnson, 1998; Haden and Johnson, 1989). However, these studies generally did not attempt to isolate the impact of specific technologies, or if they did, focused on technology adoption for enterprises that comprised a substantial portion of whole-farm business activity (e.g., dairy). Business activity from enterprises unrelated to the GE crops, such as livestock, could have interfered with the measurement of any impact that GE crop adoption had on net farm income.

Table 5—Impact of adoption of herbicide-tolerant and insect-resistant crops on yields and net returns, 1997-98

	Elasticity with respect to probability of adoption of					
	Herbicide-tolerant				Insect-resistant (Bt)	
Item	Soybean		Cotton	Corn[1]	Cotton	Corn
	1997	1998	1997[2]	1998	1997	1998
Elasticity of [3]						
Yields	+0.03	na[4]	+0.17	na	+0.21	na
Net returns[5]	0[6]	0[6]	+0.18	+0.27	+0.22	-0.34
Unit of observation	field	whole farm	field	whole farm	field	whole farm

[1] Specialized farms.
[2] Southeast region.
[3] An elasticity is the relative change in a particular impact (e.g., yields, profits) relative to a small relative change in the (probability of) adoption of the technology from current levels.
[4] Not available.
[5] Gross value of production minus variable cost (chemicals and seed expenses).
[6] Statistically innsignificant underlying coefficient.

Table 6—Elasticities of net returns with respect to the probability of GE crop adoption among specialized corn farms, by region, 1998

	Net returns	Net returns
Region	Herbicide-tolerant corn	Bt corn
U.S.	0.27	-0.34
Eastern Heartland	0.41	-0.46
Western Heartland	0.19	-0.27
Northern Crescent	0.17	-0.24*
Prairie Gateway	0.31*	-0.32*
Other regions	0.19	-0.49*

*Indicates that underlying coefficient is not statistically significantly different from that of the Eastern Heartland region.

by 10 percent, returns declined by 3.4 percent. This effect was much less in the western Heartland than the eastern (elasticity of -0.27 versus -0.46). Corn borer pressure is greater in portions of the western Heartland, as are the benefits of its relief.

Interpretation of Results on Adoption and Net Returns

Perhaps the biggest issue raised by these results is how to explain the rapid adoption of GE crops when farm financial impacts appear to be mixed or even negative. Both herbicide-tolerant cotton and Bt cotton showed positive economic results, so rapid growth in adoption is not surprising in these cases. However, since adoption of herbicide-tolerant corn appears to improve farm financial performance among specialized corn farms, why is its adoption relatively low? Even more puzzling, the adoption of herbicide-tolerant soybeans and Bt corn has been rapid, even though we could not find positive financial impacts in either the field-level nor the whole-farm analysis.

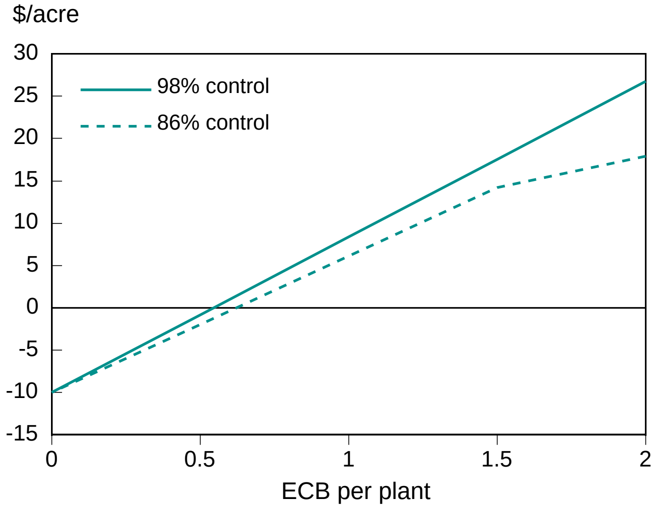
The financial benefits of adopting herbicide-tolerant corn may be due in part to seed companies setting low premiums (including technology fees) relative to conventional corn varieties in an attempt to expand market share. Also, the limited acreage on which herbicide-tolerant corn has been used is likely acreage with the greatest comparative advantage for this technology, boosting its financial benefits.

For herbicide-tolerant soybeans, the nonsignificant economic impact obtained in this study, using both 1997 field data and 1998 whole-farm data, is consistent with findings from other recent producer surveys (Duffy, 2001; Couvillion et al., 2000). For example, Duffy concludes that there is essentially no difference in returns from using herbicide-tolerant soybeans versus traditional (nontolerant) soybeans. This suggests that, given the high extent of adoption of herbicide-tolerant soybeans, other considerations may be motivating farmers.

A primary motivation may be the simplicity and flexibility of the herbicide-tolerant program (Carpenter and Gianessi, 1999), which allows growers to use one product instead of several herbicides to control a wide range of both broadleaf and grass weeds, and also makes harvest “easier and faster” (Duffy, 2001). [23] Herbicide-tolerant crops also fit into ongoing trends toward postemergence weed control, conservation tillage practices, and narrow row spacing. In addition, the window of application for glyphosate is wider than for other postemergence herbicides, allowing growers to treat later with less concern about getting poor weed control or injuring the crop. Because glyphosate has no residual activity, carryover restrictions are not a problem, giving growers more rotation options. Glyphosate is also effective at controlling weeds that are resistant to other classes of herbicides (Carpenter and Gianessi, 1999).

Figure 8

Potential returns to Bt corn



Source: Data from Rice and Pilcher (1998).

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[23] The simplicity and flexibility of pest control programs are difficult to measure and quantify from survey data. Management (operator) time used in supervising production may be an indicator of the relative convenience of alternative production systems, but a meaningful measure of management time dedicated to a particular technology and crop could not be obtained from the data.

The economic potential of Bt corn on an individual farm is more difficult to evaluate because returns to Bt corn are realized only if the density of European corn borer (ECB) is sufficient to cause economic losses greater than the premium paid for the Bt seed (fig. 8). This requires farmers to forecast infestation levels and input and corn prices before planting, prior to observing an infestation. By one account, only 25 percent of corn acreage was infested with ECB at a treatable level in 1997 (Pike, 1999). This would conform with Bt corn adoption rates of 19 percent of the corn acreage in 1998 and 26 percent in 1999 (fig. 1).

Our results show that, on the margin, the adoption of Bt corn had a negative impact on the farm financial performance of specialized corn farms in 1998. This suggests that Bt corn may have been used on some acreage where the value of ECB protection was lower than the Bt seed premium. This "overadoption" may derive from annual variations in ECB infestations, as well as poor forecasts of infestation levels, corn prices, and yield losses due to infestations.[24] Overadoption may also arise from the desire of some risk-averse farmers to insure against ECB losses.

Limitations

Our results should be interpreted carefully since just 2 years of data were examined. The financial impacts of GE crops vary with several factors, most notably annual pest infestations, seed premiums, prices of alternative pest control programs, and any premiums paid for segregated crops. These factors will likely continue to change over time as technology, marketing strategies for GE and conventional crops, and consumer perceptions of GE crops evolve.

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[24] With Bt corn adoption slipping to 19 percent in 2000 and 2001, producers may be responding to lower returns in previous years.

Adoption and Pesticide Use

A complete analysis of environmental benefits and risks of GE crop adoption is beyond the scope of this report as it would need to quantify a range of factors (such as soil, geology, vegetation, and weather conditions), and data are not available for many of them. This section explores the potential impacts on the environment from GE crops that occur via pesticide use and changes in tillage practices.

Changes in pesticide use associated with the adoption of GE crops are surely an important effect of GE crops (Royal Society, 1998; Henry A. Wallace Center, 2000). A poll of farmers and consumers in August 1999 indicated that 73 percent of consumers were willing to accept biotechnology as a means of reducing chemical pesticides used in food production. Also, 68 percent said that farm chemicals entering ground and surface water was a major problem (Farm Bureau/Philip Morris Gap Research, 2000). And more recently, a survey of consumer attitudes suggested that 70 percent of consumers would be likely to buy a variety of produce "if it had been modified by biotechnology to be protected from insect damage and required fewer pesticide applications" (IFIC Foundation, 2001).

Pesticide Use Patterns

Herbicides constitute the largest pesticide category in U.S. agriculture. Corn is the largest herbicide user, and 96 percent of the 62.2 million acres devoted to corn production in the 10 major corn-producing States were treated with more than 164 million pounds of herbicides in 1997 (USDA, NASS/ERS, 1998). Soybean production in the United States also uses a large amount of herbicides—97 percent of the 66.2 million soybean acres in the 19 major producing States were treated with more than 78 million pounds of herbicides in 1997 (USDA, NASS/ERS, 1998). Cotton production relies heavily upon herbicides to control weeds, often requiring applications of two or more herbicides at planting and postemergence herbicides later in the season (Culpepper and York, 1998). Close to 28 million pounds of herbicides were applied to 97 percent of the 13 million acres devoted to upland cotton production in the 12 major cotton-producing States in 1997 (USDA, NASS/ERS, 1998).[25]

Cotton production also uses a large amount of insecticides, with 77 percent of upland cotton acres (in the 12 major producing States) treated with 18 million pounds of insecticides in 1997 (USDA, NASS/ERS, 1998).[26] While only 30 percent of the corn acres received insecticides in the 10 major corn-producing States in 1997, the amount of these insecticides exceeded 13 million pounds (USDA, NASS/ERS, 1998).

Pesticide use on corn and soybeans has declined since the introduction of GE corn and soybeans in 1996 (fig. 9). Field tests and enterprise studies have analyzed the agronomic, environmental, and economic effects of adopting GE crops, including actual pesticide use changes associated with using GE crops (McBride and Brooks, 2000; Fernandez-Cornejo, Klotz-Ingram, and Jans, 1999, 2002; Giannessi and Carpenter, 1999; Culpepper and York, 1998; Marra et al., 1998; Falck-Zepeda and Traxler, 1998; Fernandez-Cornejo and Klotz-Ingram, 1998; Gibson et al., 1997; ReJesus et al., 1997; Stark, 1997). Many of these studies have suggested that insecticide use has (or will) decline with the adoption of Bt varieties and that herbicide use is reduced with herbicide-tolerant varieties.

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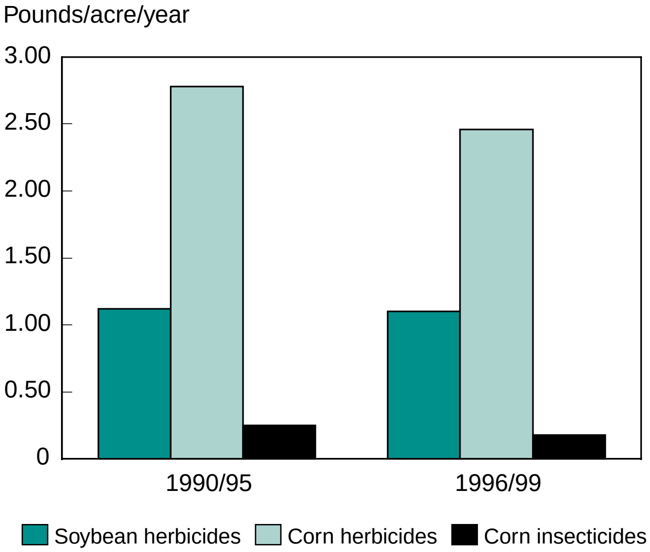
[25] Atrazine was the top herbicide used in corn in 1997, as farmers applied more than 47 million pounds of this chemical. Metolachlor was second (nearly 44 million pounds applied), followed by acetochlor (28 million pounds) and cyanazine (16 million pounds). Pendimethalin was the top herbicide used on soybeans, as farmers applied more than 17 million pounds in 1997. Glyphosate, use of which grew substantially over 1996 levels, was second (15 million pounds), followed by trifuralin (12 million pounds) and metolachlor (9 million pounds). Increased use of glyphosate has corresponded with the growth of herbicide-tolerant crop programs that use glyphosate as the primary herbicide. Trifuralin was the top herbicide applied on cotton in 1997 (5.5 million pounds), followed closely by MSMA (4.9 million pounds) and fluometuron (4.9 million pounds) (USDA, NASS/ERS, 1998).

[26] Malathion was the top insecticide used on cotton, as farmers applied more than 7 million pounds of this chemical in 1997. Aldicarb was second (2.4 million pounds), followed by methyl parathion (2 million pounds), and acephate (0.9 million pounds). The top insecticides used on corn in 1997 were chlorpyrifos (5.3 million pounds), terbufos (3.2 million pounds), methyl parathion (1.5 million pounds), and carbofuran (1.5 million pounds) (USDA, NASS/ERS, 1998).

Figure 9

Pesticide use, 1990-99



Sources: Fernandez-Cornejo (2000) based on USDA data (USDA, 1991, 1992, 1993, 1994, 1995, 1996, 1997c, 1998b, 1999a, 2000a).

The use of Bt varieties has led to reductions in those insecticides previously used to treat the pests targeted by Bt. However, conventional insecticides targeting insects not affected by the toxin continue apace. With herbicide-tolerant crops, which facilitate the use of a particular herbicide such as glyphosate, adoption simply involves substitution, changing the mix of herbicides used in the cropping system.

Pesticide Measurement Issues

The ARMS provides cross-sectional data on pesticide use by producers who do and do not adopt GE crops for each year since 1996. Using the ARMS data, one could simply compare the mean pesticide use among current adopters and nonadopters of GE crops. However, differences in characteristics that affect the adoption decision may influence pesticide use decisions as well, making these simple comparisons suspect (Fernandez-Cornejo and McBride, 2000). The challenge is to find a way to control for all other sources of variation in pesticide use so that the adoption impact can be isolated. In short, what pesticides would have been used in the given year in the absence of GE adoption?

In light of this and other issues, our analysis is based on an econometric model that statistically controls for other factors that may affect pesticide use (Fernandez-Cornejo, Klotz-Ingram, and Jans, 1999). The econometric results are expressed in terms of elasticities that represent marginal changes in pesticide use for a small increase in the adoption of GE crops. These elasticities are used to calculate the changes in acre-treatments associated with the changes in adoption between 1997 and 1998 for herbicide-tolerant soybeans and cotton and Bt cotton, and between 1996 and 1997 for herbicide-tolerant corn (Heimlich et al., 2000a,b). Pesticide use data for Bt corn were unavailable. The changes in pounds of active ingredients used associated with changes in GE crop adoption are similarly calculated, but require the assumption that the rate of application remains constant as the number of acre-treatments changes.[27]

Impact of Adoption on Pesticide Use

Our analysis shows an overall reduction in pesticide use related to the increased adoption of GE crops (Bt cotton, and herbicide-tolerant corn, cotton, and soybeans; Bt corn data were not available). The decline in pesticide use was estimated to be 19.1 million acre-treatments, 6.2 percent of total treatments (fig. 10). These estimates are associated with the changes in adoption that occurred between 1997 and 1998 (except for herbicide-tolerant corn, which is modeled for 1996-97). While such changes would normally be small over a single year, the spectacular growth in biotech crop use meant that adoption increased by 160 percent for herbicide-tolerant soybeans, 150 percent for herbicide-tolerant cotton, 12 percent for Bt cotton, and 43 percent for herbicide-tolerant corn. Most of the decline in pesticide acre-treatments was from less herbicide used on soybeans, accounting for more than 80 percent of the reduction (16 million acre-treatments).

The estimated active ingredients applied to corn, soybean, and cotton fields also declined by about 2.5 million pounds, altough the total herbicide pounds used on soybeans actually increased as glyphosate was substituted for conventional herbicides. Once the results are broken down by type of herbicide, the data indicate that an estimated 13.4 million pounds of glyphosate substituted for 11.1 million pounds of other synthetic herbicides.[28]

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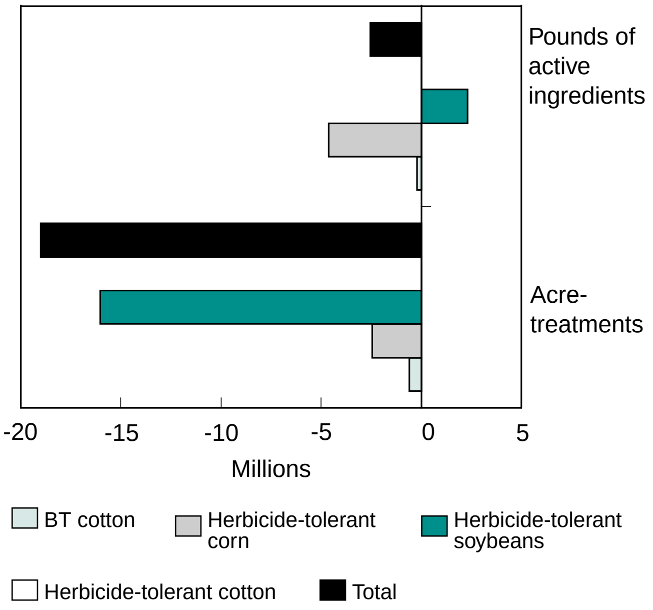
[27] This is a conservative assumption. See also note 28.

[28] As noted before, this estimate assumes constant application rates. Additional econometric estimates for adoption of herbicide-tolerant soybeans, relaxing the constant-rate assumption, showed a minimal change in the total pounds of herbicide active ingredients resulting from the substitution of glyphosate for other herbicides (Fernandez-Cornejo, Klotz-Ingram, and Jans, 2002).

Figure 10

Change in pesticide use, 1997-98



Note: Change in pesticide use from the adoption of herbicide-tolerant cotton was not significant.

Source: USDA (Heimlich et al. 2000b).

Pesticide Toxicity and Persistence

The changing mix of pesticides that accompanies adoption complicates the analysis because toxicity and persistence in the environment vary across pesticides. The term herbicide or insecticide refers to a multitude of heterogeneous products. Thousands of formulations (commercial forms in which the pesticide is sold) are used. These formulations are mixtures of active chemicals (active ingredients) and inert materials, used to improve safety and facilitate storage, handling, or application. Hundreds of chemical products are used as active ingredients. Each active ingredient has not only a different spectrum of pest control and potency, but also has a different impact on human health and the environment (Fernandez-Cornejo and Jans, 1995). Given this, it seems insufficient to report pesticide use by adding the quantities of all pesticides applied, even if expressed in pounds of active ingredient. For this reason, other measures are used such as acre-treatments and proxies for the “impact” of pesticides on human health and the environment.

Consider the most widely used GE crop, herbicide-tolerant soybeans. The adoption of herbicide-tolerant soybeans leads to the substitution of glyphosate for previously used herbicides. These crops are designed to allow farmers to limit herbicide treatments to as few as a single postemergence application of glyphosate, while a conventional weed control program can involve multiple applications of several herbicides. In addition, and more importantly, herbicide-tolerant crops often allow farmers to use more benign herbicides.

Glyphosate binds to the soil rapidly, preventing leaching, and is biodegraded by soil bacteria (Malik et al., 1989). In fact, glyphosate has a half-life in the environment of 47 days (Wauchope et al., 1993), compared with 60-90 days for the herbicides it commonly replaces. In addition, glyphosate has extremely low toxicity to mammals, birds, and fish (Malik et al., 1989). The herbicides that glyphosate replaces are 3.4 to 16.8 times more toxic, according to a chronic risk indicator based on the EPA reference dose for humans. Thus, the substitution caused by the use of herbicide-tolerant soybeans results in glyphosate replacing other synthetic herbicides that are at least three times as toxic and that persist in the environment nearly twice as long.

Soil Losses and Runoff

Availability, since the 1980s, of postemergent herbicides that could be applied over a crop during the growing season has facilitated the use of no-till farming practices, since weeds could be controlled after crop growth without tilling the soil. The use of herbicide-tolerant crops (particularly soybeans) has intensified that trend since it often allows a more effective and less costly weed control regime than using other postemergent herbicides (Carpenter and Gianessi, 1999).

The impact of conservation tillage (including no-till, ridge-till, and mulch-till) in controlling soil erosion and soil degradation is well documented (Edwards, 1995; Sandretto, 1997). By leaving substantial amounts of residue evenly distributed over the soil surface, conservation tillage (1) reduces soil erosion by wind; (2) reduces soil erosion by water (by reducing the kinetic impact of rainfall); (3) increases water infiltration and moisture retention; (4) reduces surface sediment and water runoff; and (5) reduces chemical runoff. Thus, by facilitating the use of conservation tillage (or no-till in particular), the adoption of herbicide-tolerant crops may reduce soil losses and runoff. However, there is little empirical evidence on how GE crops have affected tillage (Ervin et al., 2000).

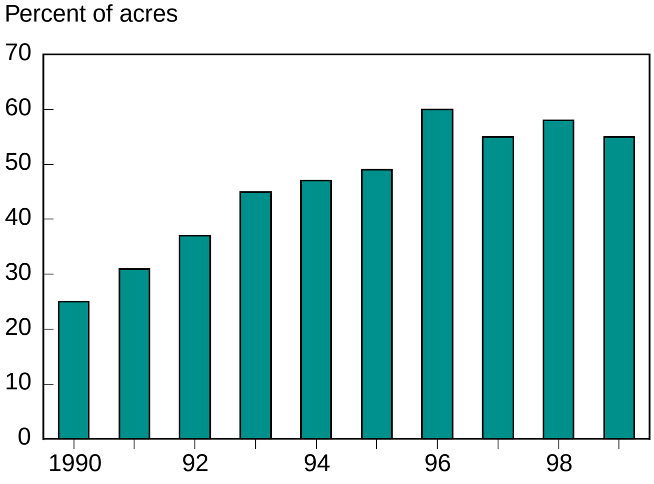
Adoption of conservation tillage for soybeans grew (at a decreasing rate) from about 25 percent of the soybean acreage in 1990 to 48 percent in 1995 (fig. 11), the 5-year period previous to the introduction of herbicide-tolerant soybeans. Growth of conservation tillage increased further in 1996, but then appears to have stagnated between 50 and 60 percent in the following years.

A larger portion of the acreage planted with herbicide-tolerant soybeans was under conservation tillage than was acreage growing conventional soybeans. According to estimates based on USDA's ARMS data, about 60 percent of the area planted with herbicide-tolerant soybeans was under conservation tillage in 1997 (fig. 12). In comparison, only about 40 percent of the acres planted with conventional soybeans were under conservation tillage the same year. Differences in use of no-till between adopters and nonadopters of herbicide-tolerant soybeans are even more pronounced: 40 percent of acres planted with herbicide-tolerant soybeans were under no-till, twice the corresponding share of farmers planting conventional soybeans.

Despite the relationship between conservation tillage and adoption of herbicide-tolerant crops, cause and effect is uncertain. Availability of the herbicide-tolerant technology may boost conservation tillage, while the use of conservation tillage may predispose farmers to adopt herbicide-tolerant seeds. Therefore, the two decisions must be considered simultaneously. An econometric model to address the simultaneous nature of these decisions (Soule and Klotz-Ingram, 2000) is used to determine the nature of the relationship between the adoption of herbicide-tolerant soybeans and no-till practices (appendix IV).

Figure 11

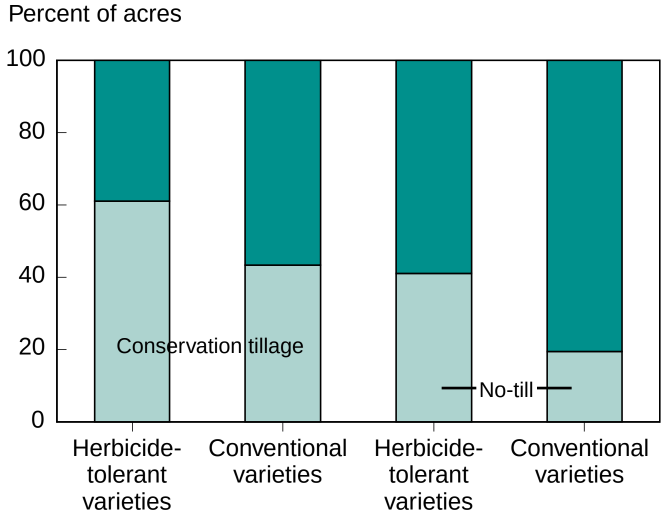
Use of conservation tillage - soybeans



Source: Fernandez-Cornejo (2000) based on USDA data (USDA, 1997a updated from ARMS).

Figure 12

Area under conservation tillage and no-till, soybeans 1997



Source: ARMS data.

According to the econometric model results, using 1997 ARMS survey data, farmers using no-till for soybeans were found to have a higher probability of adopting herbicide-tolerant seed, but using herbicide-tolerant seed did not significantly affect no-till adoption. This result seems to suggest that farmers already using no-till found herbicide-tolerant seeds to be an effective weed control mechanism that could be easily incorporated into their weed management program. On the other hand, the commercialization of herbicide-tolerant soybeans did not seem to have encouraged adoption of no-till, at least the year of the survey, 1997.

Conclusions

This report offers insight into a few of the major issues surrounding the farm-level adoption of GE crops since their recent introduction. As new technologies continue to be introduced and the issues concerning GE crops evolve, ERS is committed to providing information about how these technologies affect farmers, consumers, and the environment. Further producer surveys are being designed and implemented to monitor GE crop adoption and its impacts. The principal findings of this report are:

- The adoption of most GE crops has been rapid since these crops first became available to farmers in 1996. Adoption of herbicide-tolerant soybeans and cotton was particularly rapid, reaching 68 and 56 percent of their respective acreage in 2001. The adoption of these herbicide-tolerant crops is expected to continue growing, unless there is a radical change in consumer sentiment concerning GE crops. In contrast, the use of Bt corn peaked at about 26 percent in 1999, and retreated to below 20 percent in 2000 and 2001. Use of Bt cotton expanded to 35 percent of cotton acreage in 2000 and increased to 37 percent in 2001. Future adoption rates for Bt corn and Bt cotton are expected to increase little or possibly decrease, mainly limited by the infestation levels of their respective Bt target pests.
- The economic impact of GE crops varies by crop and type of technology. Adoption of herbicide-tolerant cotton and herbicide-tolerant corn had a positive economic impact on farms. However, adoption of herbicide-tolerant soybeans did not have a significant impact on farm financial performance. These findings were obtained from marginal analyses, meaning that the estimated financial impacts are associated with changes in adoption around the aggregate level of adoption. For example, the finding that the adoption of herbicide-tolerant soybeans did not have a significant impact on farm net returns in 1998 implies that an increase from the average adoption rate (45 percent of acreage) in 1998 would not have a significant impact on net returns.
- The use of herbicide-tolerant soybeans was quite profitable for some farms, but the profitability depended specifically on the types of weed pressures faced on the farm (Bullock and Nitsi, 2001). Farms for which the GE technology provides the highest relative profitability are likely to be the first adopters; farms for which factors other than profitability (such as the simplicity and flexibility of the herbicide-tolerant crops) are driving adoption tend to be later adopters. However, these factors are not quantified in our analysis (nor in other analyses using standard measures of profitability) of net returns to management.
- Adoption of Bt cotton had a positive economic impact on farms, but Bt corn had a negative impact. Bt corn may have been used on some acreage where the value of protection against the European corn borer (ECB) was less than the Bt seed premium. This seeming “overadoption” of Bt corn may be due to annual variations in ECB infestations as well as poor forecasts of infestation levels, corn prices, and yield losses due to infestations. In addition, some risk-averse farmers may have desired to insure against losses due to the ECB.
- The adoption of GE crops has been associated with a small but statistically significant reduction in aggregate pesticide use. While the substitution induced by the use of herbicide-tolerant soybeans results in a small overall change in pounds of herbicides, glyphosate replaces other synthetic herbicides that are at least three times as toxic to humans and that persist in the environment nearly twice as long as glyphosate.

As in all studies, the results presented in this report should be interpreted carefully, especially since the impact studies are based on just 2 years of survey data (1997 and 1998). The impacts of GE crops vary with several factors, most notably annual pest infestations, seed premiums, prices of alternative pest control programs, and any premiums paid for segregated crops. These factors will continue to change over time as technology, marketing strategies for GE and conventional crops, and consumer perceptions of GE crops evolve and new technologies are introduced. Also, the results are heavily dependent on the quality of the survey data. Survey data are influenced by nonsampling errors introduced by enumerators, respondents, and questionnaire design. While nonsampling errors are not measurable, efforts were made throughout the survey design and implementation to minimize these errors.

All in all, we conclude that there are tangible benefits to farmers adopting first-generation GE crops. Not all of the benefits are reflected in standard measures of net returns. But in looking at farm-level impacts, it appears that farmers are, at least, not being disadvantaged by the advent of GE pest and herbicide-resistant seed.

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Appendix I: A Dynamic Diffusion Model for GE Crops

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:

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

where Z is the proportion of the total population that have adopted the innovation at time t, K is the ceiling value or longrun 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 percent of firms, although in agriculture the percentage often refers to acreage under adoption, e.g., Knudson, 1991). As Griliches 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 for 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) observe, any unimodal distribution function will generate a (cumulative) S-shaped curve.

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

$$dZ(t)/dt = g(t)\ [K - Z(t)] \qquad (2)$$

where $g(t)$ is called 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 $g(t)= \phi\, Z(t)$ 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 et al., 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:

$$dZ(t)/dt = \phi\, Z(t)\ \ [K - Z(t)] \qquad (3)$$

Integrating (3), we obtain the logistic,

$$Z = K/[1+e^{(-a-\phi\, t)}] \qquad (4)$$

Making a log-linear (or logit) algebraic transformation of the adoption equation, we obtain $ln[Z/(K\text{-}Z)] = a + \phi\, t$ (Griliches, 1957), where the slope parameter ϕ 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 $t=0$, $a = ln[Z/(K\text{-}Z)]$. The ceiling K is the longrun upper limit on adoption. Technically, the diffusion rate $dZ(t)/dt$ approaches to zero as Z approaches to 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 percent of the ceiling level. The Gompertz model is similarly obtained from equation (3) simply by substituting the log of K and log of $Z(t)$ for the two terms in braces and integrating (Mahajan and Peterson, 1985, pp. 19-20).

Static and Dynamic Models. Static diffusion models, following the terminology of Knudson (1991), are growth models that 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 are considering. 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: (1) an individual either adopts or does not adopt; (2) there is a fixed, finite ceiling K; (3) the rate coefficient of diffusion is fixed over time; (4) the innovation is not modified once introduced, and its diffusion is independent from the diffusion of other innovations; (5) one adoption is permitted per adopting unit and this decision cannot be rescinded; and (6) a social system's geographical boundaries stay constant over the diffusion process. While 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 that N and K are constant (independent of t). In this case, the logit transformation of the adoption equation $ln[Z/(K-Z)] = a + \phi t$ 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. But its usefulness is limited since the parameters that 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., ϕ, 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 $S(t)$ of exogenous factors believed to influence adoption (Jarvis, 1981; Knudson, 1991). Two drawbacks of the variable-ceiling logistic model are that there is no guarantee that the ceiling will stay at theoretically justifiable levels, or that the equation will even converge when the data are extremely nonlinear. The second version of the dynamic logistic model is the variable-slope logistic model, 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 method 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 percent or lower). This model is easier to estimate and does not have the problems of the variable-ceiling logistic model for estimations using non-loglinear data (e.g., nonconvergence, unacceptable results such as K higher than 100 percent).

Dynamic 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." 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***) that denote demand conditions for GM crops. Thus we have: $\phi = \phi_0 + \boldsymbol{\phi_1}'\boldsymbol{R} + \boldsymbol{\phi_2}'\boldsymbol{S}$. Substituting the variable slope in (4), we obtain:

$$Z = K / \{1+e^{[-a-(\phi_0 + \boldsymbol{\phi}_1' R + \boldsymbol{\phi}_2' \mathbf{S})]t}\} \qquad (5)$$

Making the logit transformation and adding a vector of regional dummy variables (***D***) to account for regional differences in technology (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 ε, we arrive at the estimating equation:

$$ln\,[Z/(K - Z)] = a + (\phi_0 + \boldsymbol{\phi}_1' \mathbf{R} + \boldsymbol{\phi}_2' \mathbf{S})\, t + \gamma' \boldsymbol{D} + \varepsilon = a + \phi_0\, t + \boldsymbol{\phi}_1' \boldsymbol{R}\, t + \boldsymbol{\phi}_2' \boldsymbol{S}\, t + \gamma' \boldsymbol{D} + \varepsilon \qquad (6)$$

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), proposals of mandatory labeling 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, plans by some U.S. food processors (Heinz, Gerber, Frito-Lay) and several Japanese brewers to stop using biotech ingredients in some of their products. Appendix table 1.1 shows a summary of selected market events extracted from Dohlman, Hall, and Somwaru (2000).

Given the large number of components of the vector of "market events" that impacted the demand of GE crop products in recent years, and to conserve degrees of freedom, we specify a proxy that captures most of the information contained in the vector ***R*** of market events. The proxy selected is an index of stock prices of agricultural biotechnology 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 information." Moreover, an earlier study by Bjornson (1998) had shown 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 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 once a year. In this context, the stock-price index assumes the role of leading indicator of demand conditions (for example, an import ban that occurs in November will be incorporated in the stock prices immediately, but will only translate into planted acreages/adoption in the 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 that 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 foretell an increase in the demand of genetically engineered crops. Consequently, the R term is expected to have a positive coefficient. Regarding the crop-specific effects of S, an increase in insecticide price is expected to lead to an increase in the incentive for adoption of 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.

Ceilings. We specify ceilings for the adoption of different genetically engineered crops by considering 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 percent of the corn acres infested with the European corn borer (at a treatable level) relative to the planted corn acreage. Appendix table 1.2 shows 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-percent refugia, which is the figure most commonly recommended, was used in this study (Henderson, 1999; EPA, 1999). Similarly, for Bt cotton, the ceiling is obtained from a 3-year average of recent infestation levels of cotton fields, i.e., the percentage of the cotton acres infested by the bollworm, budworm, and pink bollworm. The results are shown in appendix table 1.3. This ceiling is also reduced by the refugia requirements. Alternative scenarios are obtained assuming infestation levels 30 percent higher and 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. 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 percent of U.S. production in recent years (appendix table 1.4), we examined various scenarios considering different percentages of U.S. exports for which GE soybeans remained eligible. In one extreme case, it was assumed that 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 GE soybeans were also examined. As food safety and consumer concerns in the export market are not restrictive for herbicide-tolerant cotton, we follow Rogers (1983) and use a ceiling of 90-percent adoption. A 70-percent ceiling is used to examine the sensitivity of the results to the ceiling specification. Demand restrictions in the export market are not considered for Bt cotton, since consumer concerns do not extend to cotton.[1]

To summarize, the estimation of the dynamic logit regression (for the base cases) is based in 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 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 percent. We re-estimate each regression for a set of alternative ceiling values.

Data and Estimation. Adoption data for 1996-98 are obtained from the ARMS surveys, conducted through onsite 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 Objective Yield Survey (OYS) and the June Agricultural Survey. The OYS was used to obtain adoption data for 1999 (USDA, NASS, 1999c). The June Survey provided adoption data for 2000 (USDA, NASS, 2000b). The crops included in the surveys are corn, soybeans, and upland cotton. A summary of these data sources is presented in box 1 (pp. 5-7). To define regional dummies, this analysis uses the new set of eight farm resource regions, recently constructed by ERS, depicting geographic specialization in production of U.S. farm commodities.

To estimate the expected prices of chemical inputs (glyphosate, other herbicides, insecticides), we use the actual prices paid lagged 1 year, obtained from USDA, NASS (2000a, c, d). The stock price index of ag biotech 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).[2] The index is deflated by the S&P 500 index and lagged 1 year.

Maximum likelihood methods are used to estimate the regressions. Time is defined as the calendar year minus 1995. Weighted least squares estimation techniques are used to correct for heteroscedasticity because data were aggregated (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 a measure of the sensitivity of the results to the precise ceiling specification.

Results. The results of the dynamic logit parameter estimates for Bt corn, Bt cotton, and herbicide-tolerant soybeans and cotton are presented in appendix table 1.5 for the base cases. The fit of the dynamic logistic model

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[1] We do not consider export restrictions for Bt corn, because any such restrictions will be less binding than those implied by actual ECB susceptibility and/or infestation levels (compare appendix table 1.2 regarding corn borer infestations to appendix table 1.4 regarding the importance of corn exports).

[2] For some multiproduct firms (Monsanto, Aventis, Dupont), GE seeds are only a portion of their business and their 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 ag biotech 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 (e.g., see article in the *New York Times*, Jan. 25, 2001, part 7: "..with the stock in the doldrums because of its struggles with agricultural biotechnology, Monsanto..."). And many firms are severing agricultural biotech activities from their other businesses (e.g., Monsanto IPO from Pharmacia).

appears to be good. For the base cases, the adjusted R-square ranges from 0.80 to 0.96. Overall, the dynamic diffusion model appears to fit reasonably well for Bt crops. Further, the significance of nontime exogenous variables in both equations suggests that the use of a dynamic specification rather than a static specification is warranted. In particular, the coefficients of the relevant market variables have the expected sign for Bt corn and Bt cotton. For both Bt crops (appendix table 1.5), the diffusion rate is positively and significantly related to the biotech stock price index, corroborating that 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 as insecticide prices rise the incentive to adopt the (substitute) Bt crops increases. 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 (appendix table 1.5). This sign may have resulted from the many advantages of herbicide-tolerant soybeans perceived by growers, which rapidly increased their adoption of herbicide tolerant soybeans between 1995 and 1998 despite glyphosate prices rising 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. For this reason, the effect of the negative correlation between prices and adoption in 2000 was weaker than that of the positive correlation of the previous 4 years, giving an overall positive sign.

For the herbicide-tolerant crops, the biotech stock price index is not significantly related to adoption, indicating that planting decisions regarding these crops are not correlated with events driven by consumer 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 (e.g., appendix table 1.1), and in general, most media coverage is related to Bt corn. Moreover, despite that corn and soybean growers are essentially the same people, planting decisions for Bt corn and herbicide-tolerant soybeans may differ 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 about planting decisions among Iowa corn-soybean farmers reported by Alexander, Fernandez-Cornejo, and Goodhue (2000a). 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 concerns about using GE crops.

Appendix table 1.1—Selected market events correlated with the index of ag biotech firms

Event	Date
◆ Press release details journal article finding that useful predatory insects could be harmed by Bt corn	08/21/98
◆ EU labeling regulation 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 that biotech corn cross-pollinated adjacent field of conventional corn released	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 3 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).

Appendix table 1. 2— Infestation of corn fields at a treatable level by the European corn borer, 1997 crop year

State/region	Infested area Ha[1]	Planted acres[2]	Percent acreage infested
	---------- *Thousands*	----------	*Percent*
Heartland			
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			
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	43.8
Other			
Kentucky	34.5	1,150	
North Carolina	54.5	870	
North Dakota	77.3	590	
	166.3	2,610	15.70
All major States	6,314.2	64,630	24.13

[1] From Pike (1999).
[2] USDA, NASS (1999c).

Appendix table 1.3—Infestation of cotton fields by bollworm, budworm, and pink bollworm, 1996-98

Pest/year	Acres infested[1]	Acres infested[2]	Percentage of acreage infested
	---------- *Thousands* ----------		*Percent*
Boll/budworms			
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[3]			
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

[1] From Williams et al. (1997, 1998, 1999).

[2] USDA, NASS (1999c).

[3] Assuming no overlap

Appendix table 1.4—Total exports as a percent of U.S. production

Crop/item	1995/96	1996/97	1997/98	1998/99
Corn				
Production, *mil. bushels*	7.400	9.233	9.207	9.759
Exports, *mil. bushels*	2.228	1.797	1.504	1.981
Percent	30.1	19.5	16.3	20.3
Soybeans				
Production, *mil. bushels*	2.177	2.380	2.689	2.741
Exports, *mil. bushels*	0.851	0.882	0.873	0.801
Percent	39.1	37.1	32.5	29.2

Source: USDA, ERS, 2000b.

Appendix table 1.5—Dynamic logit parameter estimates

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	0.1633
Adjusted R-Squared	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-Squared	0.799			
C. Herbicide-tolerant soybeans, ceiling calculated assuming no GE exports				
Intercept	-3.89182	0.46479	-8.37	<.0001
Time	-0.81329	0.26627	-3.05	0.0080
HEARTLAND	-0.07828	0.14632	-0.53	0.6005
MISSIPORTAL	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
Pindex*t	-0.58520	0.62909	-0.93	0.3670
Pglytoherb*t	3.13419	1.21704	2.58	0.0211
Adjusted R-Squared	0.959			
D. Herbicide-tolerant cotton, ceiling equal to 90 percent				
Intercept	-17.48254	6.67041	-2.62	0.0278
Time	2.13720	1.10169	1.94	0.0843
MISSPORTAL	0.16209	0.27624	0.59	0.5718
SOUTHSEA	0.37307	0.26178	1.43	0.1879
Pbindex*t	-0.55928	0.65087	-0.86	0.4125
Pglytoherb*t	12.35018	6.19381	1.99	0.0773
Adjusted R-Squared	0.953			

Note:
TIME is the time in years, 1995=0.
HEARTLAND, NCRESCENT, PGATEWAY, MISSPORTAL, SOUTHSEABOARD, FRUITFULR, EUPLANDS represent dummy variables equal to one for the heartland region, northen crescent region, praire gateway, Missisippi portal, southern seaboard, fruitful rim, and uplands region, repectively.
PBINDEX is an index of ag biotechnology stock prices.
PINSECT is the insecticide price index.
PGLYPHERB is the price ratio of glyphosate to other herbicides.
PBINDEX_t is an interaction term equal to the product of PBINDEX and TIME.
PINSECT_t is an interaction term equal to the product of PINSECT and TIME.
PGLYPHERB_t is an interaction term equal to the product of PGLYPHHERB and TIME.

Appendix II. An Empirical Tobit Model To Examine the Factors Influencing Adoption

A Tobit model (Tobin, 1958) was used to model factors that influence adoption of genetically engineered crops. This method estimates the likelihood of adoption and the extent (i.e., intensity) of adoption. The Tobit approach has been applied in previous studies of agricultural technology adoption, including studies of conservation adoption (Norris and Batie, 1987; Gould et al., 1989) and the adoption of alternative crop varieties (Adesina and Zinnah, 1993).

A two-limit Tobit model was used. The two-limit Tobit, originally presented by Rossett and Nelson (1975) and discussed in Maddala (1992) and Long (1997), is appropriate since the dependent variable is the proportion of the acreage with the technology; thus, the dependent variable must be between 0 and 1. The two-limit Tobit model can be represented as:

$$y_i^* = \beta' x_i + \in_{\mathrm{i}} \qquad (1)$$

where y_i^* is a latent variable (unobserved for values smaller than 0 and greater than 1) representing the use of the technology; **x** is a vector of independent variables, which includes the factors affecting adoption; β is a vector of unknown parameters; and $\in_{\mathrm{i}}$ is a disturbance assumed to be independently and normally distributed with zero mean and constant variance F; and i = 1, 2,…*n* (n is the number of observations). Denoting y_i (the proportion of acreage on which the technology is used) as the observed dependent (censored) variable:

$$y_i = \begin{cases} 0 & \text{if} \quad y_i^* \le 0 \\ y_i^* & \text{if} \quad 0 \le y_i^* \le 1 \\ 1 & \text{if} \quad y_i^* \ge 1 \end{cases} \qquad (2)$$

Using the two-limit Tobit, the extent of adoption was regressed against proxies for various factors hypothesized to influence producer adoption.

The McDonald-Moffit Decomposition for a Two-Limit Tobit. Unlike traditional regression coefficients, the Tobit coefficients cannot be interpreted directly as estimates of the magnitude of the marginal effects of changes in the explanatory variables on the expected value of the dependent variable. In a Tobit equation, each marginal effect includes both the influence of the explanatory variable on the probability of adoption as well as on the intensity of adoption. More explicitly, as Gould et al. (1989) observe, the total (marginal) effect takes into consideration that a change in an explanatory variable will affect simultaneously the number of adopters and the extent of adoption by both current and new adopters.

To obtain the decomposition for the case of a two-limit Tobit, begin with equation (1). Given the assumption that the disturbance $\in_{\mathrm{i}}$ is independently and normally distributed with zero mean, the expected value of the latent variable for the two-limit Tobit is $E(y^* | x) = \beta' x$ and $\partial E(y^* | \mathbf{x}) / \partial x_k = \beta_k$. However, the conditional expected value of the truncated outcome is (Long, 1997; Maddala, 1992) is:

$$E(y | \boldsymbol{x}, L < y^* < U) = \boldsymbol{\beta x} + \sigma \frac{\phi(Z_L) - \phi(Z_U)}{\Phi(Z_U) - \Phi(Z_L)} \qquad (3)$$

where *L* and *U* denote the lower and upper limit, respectively; $Z_L = (L - \boldsymbol{\beta x})/\sigma$ and $Z_U = (U - \boldsymbol{\beta x})/\sigma$; $\Phi(.)$ and $\phi(Z)$ are the cumulative distribution and density function for the standard normal. The expected value of the dependent variable (observed outcome) (Long, 1997) is:

$$E(y | x) = L \cdot Pr(y = L | x_i) + E(y | x, L < y^* > U, x) \cdot Pr(L < y^* > U | x_i) + U \cdot Pr(y = U | x_i) \qquad (4)$$

Substituting the expressions for $Pr(y = L | x_i) = \Phi(Z_L)$, $Pr(y = U | x_i) = 1 - \Phi(Z_U) = \Phi(-Z_U)$, into the equation above and taking the derivative, one obtains the marginal effect:

$$\begin{aligned} \frac{\partial E(y \mid \boldsymbol{x})}{\partial x_k} &= E(y \mid x, L < y^* < U) \cdot \left[\frac{\partial [\Phi(Z_U) - \Phi(Z_L)]}{\partial X_k} \right] \\ &+ [\Phi(Z_U) - \Phi(Z_L)] \cdot \left[\frac{\partial E(y \mid x, L < y^* < U)}{\partial X_k} \right] \\ &+ \frac{\partial \Phi(-Z_U)}{\partial x_k} \end{aligned} \tag{5}$$

Equation (5) is the extension of the McDonald-Moffit decomposition for the case of a two-limit Tobit. It decomposes the total marginal effect of a change in an independent variable x_k on the expected value of the extent of adoption (i.e., the percent of the acreage under the technology) into three components:

(i) The change in the probability of adoption weighted by the conditional expected value of the percent acreage under adoption given that the farmer has adopted,

(ii) The change in the percent acreage under adoption for farmers that are already adopting weighted by the probability of adoption, and

(iii) The change in the probability of adopting on 100 percent of the acreage.

Substituting the expression for $E(y \mid \boldsymbol{x}, L < y^* < U)$ from equation (3), setting the lower limit L=0 and the upper limit U=1 and taking the derivatives, recalling that $\partial \Phi(Z)/\partial x_k = \phi(Z) \cdot (\beta_k/\sigma)$, one obtains the expression for the three components of the marginal effect:

$$\begin{aligned} \frac{\partial E(y \mid \boldsymbol{x})}{\partial x_k} &= \left\{ (\beta x + \sigma \left[\frac{\phi(Z_L) - \phi(Z_U)}{\Phi(Z_U) - \Phi(Z_L)} \right] \right\} \cdot [\phi(Z_L) - \phi(Z_U)] \\ &+ [\Phi(Z_U) - \Phi(Z_L)] \cdot \beta_k \cdot \left\{ 1 + \frac{Z_L \phi(Z_L) + Z_U \phi(Z_U)}{\Phi(Z_U) - \Phi(Z_L)} - \frac{[\phi(Z_L) - \phi(Z_U)]^2}{[\Phi(Z_U) - \Phi(Z_L)]^2} \right\} + \\ &+ \beta_k [\phi(-Z_U)/\sigma] \end{aligned} \tag{6}$$

Simplifying, one obtains the total marginal effect: $\partial E(y \mid \boldsymbol{x})/\partial x_k = \beta_k . [\Phi(Z_U) - \Phi(Z_L)]$.

Data and Estimation. Data used to estimate the Tobit model are from USDA's 1998 ARMS. The definition of a farm, and thus the target population of the ARMS, is any business that produces at least $1,000 worth of agricultural production during the calendar year. The farm population used in this study includes those that grew corn or soybeans during 1998. Appendix table 2.1 shows the number of observations in each case. The ARMS data include information about the financial condition and management of the operation; demographic characteristics; and management and marketing strategies used on the operation. Important to this study is that the survey included questions about the extent to which alternative technologies were used in the farm business. Producers were asked for each crop grown whether they planted bioengineered seed and, if so, what type of seed was planted and on how many acres it was planted. The adoption of GE crops was defined in cases where herbicide-tolerant soybeans, herbicide-tolerant corn, and Bt corn were used. The extent of adoption was defined as the proportion of total harvested corn (soybean) acres in herbicide-tolerant corn (soybeans) as well as the proportion of total corn acres in Bt corn.

A total of three Tobit adoption models were estimated using the ARMS data, one for each of the three genetically engineered crop varieties. The estimating technique was consistent with the complex survey design of the ARMS (Dubman, 2000). The LIFEREG procedure of SAS with the weight option (using the survey weights) was used to estimate the parameters. A replication approach employing the delete-a-group jackknife method was used to estimate parameter standard errors (Kott and Stukel, 1997; Kott, 1998).

Variable Specification. While technology adoption has both static and dynamic aspects, our focus is from a cross-section, point-in-time (i.e., static) perspective at the micro (i.e., individual farm) level. At this level, each farm operator is assumed to decide whether to adopt a technology and, if adopted, to choose its intensity of use. Within this context, the analysis encompasses both the farm and operator characteristics that are hypothesized to influence the decision to adopt and to what extent. We also incorporate a proxy variable to account for farm location (i.e., a proxy for climate, soil type, topography, input/equipment dealer availability, etc.) similar to Fernandez-Cornejo et al. (1994) and Green et al. (1996).

The adoption rate of GE technologies was expected to be influenced by the following sets of factors: farmer risk attitudes; farmer management resources, including education, experience, and off-farm employment; farm size, land tenure; credit reserves; farm typology; use of contracting; degree of pest infestation (for the case of Bt corn); and a regional dummy variable. While the variables are defined in appendix table 2.1, some require additional clarification.

The main focus of this study is on the role of farm size in technology adoption. Farm size is defined as the number of corn and soybean acres harvested on the operation. To allow for the possibility that the effect of farm size on adoption may vary as size changes, both linear and quadratic terms for size are included. Following Kinnucan et al. (1990), one interprets the significant coefficients on the farm size terms in the estimated model, which control for other factors, as an indication of scale dependency associated with the adoption of the technology.

Identifying and quantifying producer risk preferences is a difficult task (Feder et al., 1985). To operationalize the concept of risk preferences using farmer attributes obtained from the survey, one uses a risk index constructed according to farmers' answers to a series of questions in the ARMS survey. The construction is based on the notion that risk attitudes are reflected by farmers' attitudes toward tools used for managing risk. Moreover, as Bard and Barry (1998) show, it is more appropriate to base the analysis of issues involving risk on how farmers react to risk than their self-assessment.

Ten questions were included in the ARMS survey questionnaire to elicit farmers' attitudes toward tools used for managing risk. The questions asked whether farmers strongly agreed, agreed, neither agreed, or disagreed, disagreed, or strongly disagreed with each of 10 statements. To prevent response bias, some of the questions were worded in such a manner that strong agreement implies willingness to accept more risk while other questions are phrased such that agreement with the statement implies that the farmer is more risk adverse. Thus, typically the questions begin with either "I never" or "I usually." Subjects of the questions are having cash on hand to pay bills, use of custom work, reliance on market information to make marketing decisions, spreading commodity sales throughout the year, having adequate liability insurance, having machinery new or in good repair, believing that concentration of farming operations in one geographic area "substantially increases" total risk, having sufficient backup management/labor to carry production for emergencies, having adequate hail/fire insurance, and hedging by using futures/options (Bard and Barry, 1998).

Categories of the ERS farm typology classification based on the occupation of farm operator were also included in the model (Hoppe, Perry, and Banker, 1999). The mutually exclusive typology categories were specified as a series of dummy variables that indicate whether or not the farm was classified as limited-resource, retirement, residential lifestyle, or a nonfamily farm. Limited-resource farms are constrained by low levels of assets and household income. Retirement farms are those with operators who report that they are retired (excluding limited-resource farms). Residential lifestyle farms are those with operators who report a major occupation other than farming (excluding limited-resource farms). Nonfamily farms are those organized as nonfamily corporations or cooperatives, as well as those operated by hired managers. These categories were included in the adoption model to account for the diversity of farm types by reflecting differences in operators' expectations from farming, stage in the life cycle, and dependence on agriculture.

A credit reserve variable was specified as the maximum feasible level of debt that the farm operator could service from income (Ryan, 1999). Credit reserves are hypothesized to positively influence adoption. Genetically engineered seeds are more expensive than traditional varieties and adoption may also be influenced by the operating investment. Also included was the proportion of operator and spouse hours worked off-farm.

The use of contracting was specified using a dummy variable indicating whether or not the farm sold corn (or soybeans) under a marketing contract, or produced corn (or soybeans) under a production contract. Contracting has been used in modeling adoption to reflect the level of risk management used by producers. In the context of biotech crops, contracting may indicate that the producer has locked a market channel for the crop and thus has reduced the uncertainty that these crops would be accepted in traditional marketing channels. Producers would be more likely to adopt biotech crops if they have contracts that ensure market access. Contracting may also be an indicator of the overall level of operator management.

A measure of State infestation level for the European corn borer (ECB) was included in the Bt corn adoption model to account for variation in the perceived need for pest control. As an infestation level proxy, we used a dummy variable equal to 1 for the States with the highest infestations, and 0 otherwise. Past infestation levels of corn fields by the ECB were calculated as the percentage of the State's corn acres infested with ECB at a treatable level (obtained from Pike, 1999) relative to the planted corn acreage.

Results. Results of the Tobit analysis for the adoption of genetically engineered crops are presented in Appendix tables 2.2 and 2.3. These tables include the estimated coefficients, standard errors, and calculated marginal effects. The marginal effects are used to calculate the elasticities.

Statistically significant variables in the adoption models varied among the individual technologies. Farm size was significant in the Bt corn and herbicide-tolerant corn, but not for herbicide-tolerant soybeans. The coefficients of the quadratic terms indicate that the probability of adoption for Bt corn and precision farming increased with farm size at a decreasing rate while adoption of herbicide-tolerant corn increased linearly with size (within the range of the data). The contracting variable was significant in two of the three adoption models. The expected extent of adoption was greater on operations that utilized marketing or production contracts than for other operations. Among operator characteristics, education and experience were significant in various adoption models. The expected extent of adoption associated with two of the three technologies increased significantly as operator education increased. The expected extent of adoption of herbicide-tolerant corn and soybeans increased with operator experience. The measure of operator risk aversion was only significant in the herbicide-tolerant soybean model. The negative coefficient on the risk variable indicates that the more risk-averse producers are expected to have a higher extent of adoption for these technologies. Location of the operation outside of the primary production area was associated with a lower expected adoption for herbicide-tolerant soybeans. Among the typology variables, only the limited-resource classification was significant in the model for herbicide-tolerant soybeans, suggesting that limited-resource farms were less likely to adopt. The corresponding indicator variable shows that corn borer infestation had a significant and positive influence on the expected adoption of Bt corn. Credit reserves, off-farm work, and land tenure were not significant in any of the adoption models.

Appendix table 2.1—Variable definitions and means

Variable name	Variable definition	Mean value	
		Soybean farms	Corn farms
EDUCATION	Education of the operator: beyond high school/college = 1, 0 otherwise	0.422	0.424
EXPERIENCE	Operator experience, years on operation	23.52	23.98
CREDIT	Credit reserve (maximum debt repayment capacity), $1,000	232.8	228.2
OFF	Operator/spouse proportion of time worked off-farm	0.412	0.387
MARGINALR	Dummy variable equal to 1 if farm is located in marginal production region, 0 otherwise[1]	0.248	0.381
SIZE	Farm size, 1,000 acres of harvested soybeans/corn	0.195	0.164
SIZE_SQ	Farm size squared	0.121	0.086
TENURE	Farm tenure, ratio of owned to operated acres	0.489	0.553
RISK	Risk index, ranging from 12 (risk averse) to 48 (risk seeking)	28.63	28.38
LIMRES	Dummy variable equal to 1 if farm belongs to the “limited-resources” category of the ERS farm typology, 0 otherwise	0.042	0.042
RETIRE	Dummy variable equal to 1 if farm belongs to the “retirement” category of the ERS farm typology operator is, 0 otherwise	0.029	0.034
LIFEST	Dummy variable equal to 1 if farm belongs to the “residential/ lifestyle” category of the ERS farm typology, 0 otherwise	0.282	0.254
NONFAM	Dummy variable equal to 1 if farm belongs to the “nonfamily” category of ERS farm typology, 0 otherwise	0.026	0.022
CONTRACT	Dummy variable equal to 1 if farm uses soybeans/corn marketing or production contracts, 0 otherwise	0.121	0.131
HI_INF	Dummy variable equal to 1 if farm is in State with a high infestation level of European corn borer, 0 otherwise	na	0.248
Number of observations		2,321	1,719

[1] Marginal production regions are those outside of the primary areas where these crops are grown, defined using the ERS farm resource regions (box 1). Primary production regions for soybeans are the Heartland and Mississippi Portal. Primary production regions for corn are the Heartland and Prairie Gateway.

na = Not applicable.

Appendix table 2.2—Tobit estimates: Adoption of herbicide-tolerant soybeans, Bt corn, and herbicide-tolerant corn, 1998

Technology/ variable	Estimated coefficient	Standard error	t-statistic	Marginal effect $\partial E(y\|\mathbf{x})/\partial x_k$
Herbicide-tolerant soybeans:				
Intercept	0.10627	0.60357	0.18	—-
EDUCATION	0.40943	0.28592	1.43	0.081
EXPERIENCE	0.01234	0.00641	1.92*	0.002
CREDIT	0.00019	0.00025	0.78	0.000
OFF	0.13772	0.25491	0.54	0.027
MARGINALR	-0.38910	0.14220	-2.74**	-0.077
SIZE	0.03087	0.23659	0.13	0.006
SIZE_SQ	-0.07041	0.06751	-1.04	-0.014
TENURE	-0.35418	0.31678	-1.12	-0.070
RISK	-0.03684	0.01476	-2.50**	-0.007
LIMRES	-1.44391	0.44928	-3.21**	-0.284
RETIRE	-0.38311	0.56992	-0.67	-0.075
LIFEST	0.08242	0.32830	0.25	0.016
NONFAM	0.71062	0.42338	1.68	0.140
CONTRACT	0.36799	0.14653	2.51**	0.072
Bt corn:				
Intercept	-0.57717	0.36585	-1.58	—-
EDUCATION	0.22989	0.09624	2.39 **	0.037
EXPERIENCE	0.00384	0.00366	1.05	0.001
CREDIT	0.00011	0.00009	1.22	0.000
OFF	-0.16851	0.12394	-1.36	-0.027
MARGINALR	-0.11709	0.08728	-1.34	-0.019
SIZE	1.06147	0.25152	4.22 **	0.172
SIZE_SQ	-0.43925	0.12973	-3.39**	-0.071
TENURE	-0.09012	0.11267	-0.80	-0.015
RISK	-0.01537	0.01357	-1.13	-0.002
LIMRES	-0.02361	0.27252	-0.09	-0.004
RETIRE	-0.36465	0.31985	-1.14	-0.059
LIFEST	0.07478	0.17853	0.42	0.012
NONFAM	0.22157	0.23895	0.93	0.036
CONTRACT	0.09635	0.05515	1.77*	0.016
HI_INF	0.26938	0.10626	2.54 **	0.044
Herbicide-tolerant corn:				
Intercept	-2.24752	0.48173	-4.67**	—-
EDUCATION	0.54292	0.16289	3.33**	0.019
EXPERIENCE	0.01294	0.00651	1.99*	0.001
CREDIT	-0.00026	0.00013	-1.94*	-0.000
OFF	0.06968	0.38352	0.18	0.002
MARGINALR	-0.07962	0.13278	-0.60	-0.003
SIZE	1.16590	0.62184	1.87*	0.041
SIZE_SQ	-0.42077	0.44267	-0.95	-0.015
TENURE	-0.11399	0.30899	-0.37	-0.004
RISK	-0.01762	0.01583	-1.11	-0.001
LIMRES	0.24265	0.60202	0.40	0.008
RETIRE	-0.97222	5.22866	-0.19	-0.034
LIFEST	-0.12682	0.31294	-0.41	-0.004
NONFAM	0.25422	0.70038	0.36	0.009
CONTRACT	0.00255	0.14292	0.02	0.000

Note: Single and double asterisks (*) denote significance at the 10-percent and 5-percent levels, respectively. Using the delete-a-group jackknife variance estimator with 15 replicates, the critical t-values are 2.145 at the 5-percent level and 1.761 at the 10-percent level. —- = Not applicable.

Appendix III. Using Whole-Farm Data To Model the Financial Impact of Adoption

The impact of the adoption of GE crops on farm financial performance is assessed by statistically controlling for several other factors that may also affect financial performance. That is, the effect of economic and environmental conditions, management practices, and operator characteristics are accounted for in order to isolate the effect of GE crop adoption on farm financial performance. To control for factors other than GE crop adoption, multiple regression is used in a two-stage econometric model of adoption and the adoption impact. The first stage of the model consists of an adoption-decision model that describes what factors influence the likelihood of adopting GE crops. Results of the first stage provide input for the second stage model that is used to estimate the impact of GE crops on farm financial performance.

In this study, the first stage of Heckman's technique involves the estimation of a GE crop adoption model using the probit analysis. Estimated parameters from the probit model are then used to calculate the predicted probabilities $(\hat{P}_i)$ of adopting GE crop technology. Addressing the simultaneity and self-selectivity concerns when estimating farm net returns is accomplished by appending to the basic regression explaining financial performance the predicted probabilities $(\hat{P}_i)$ of adopting GE crop technology and the inverse Mills ratio $(\hat{\lambda}_i)$ as additional regressors, as in the following:

$$\Pi_i = \beta_0 \Sigma \beta_j X_{ij} + \gamma_1 \hat{P}_{i1} + \varsigma_{i1} \hat{\lambda}_{i1} + \varepsilon_i$$

where Π is a vector denoting net returns (see page 54 for exact measure used); *X*, a matrix of exogenous variables affecting the farm's financial performance, and ε_i is a vector of errors. This model allows for the estimation of net returns using least squares when the technology adoption decision involves only one choice. In the case when multiple and independent technology choices are involved, it can be extended to reflect these additional choices by appending both the separate predicted probabilities reflecting these choices.

Data. The data used in this study are from phase 3 of USDA's 1998 Agricultural Resource Management Study (ARMS) described in Box 3. The definition of a farm, and thus the target population of the ARMS, is any business that produces at least $1,000 worth of agricultural production during the calendar year. The farm population of interest in this study includes those that grew corn or soybeans during 1998. The ARMS data include information about the financial condition and management of the operation; demographic characteristics; and management and marketing strategies used on the operation. Important to this study is that the 1998 survey included questions about the extent to which GE technologies were used in the farm business. Producers were asked for each crop grown, whether they planted GE seed and, if so, what type of seed was planted and on how many acres it was planted. The adoption of GE crops was defined in cases where herbicide-tolerant soybeans, herbicide-tolerant corn, and Bt corn were used. The analysis of the impact of the adoption of GE corn (soybeans) was conducted on two segments of the farm population: (1) operations that harvested one or more acres of corn (soybeans), and (2) operations that specialized in the production of corn (soybeans). Specialized corn (soybean) farms were defined as those on which corn (soybeans) accounted for more than 50 percent of the total value of farm production. The population of specialized farms was examined in addition to all growers because the impact of GE technologies on farm financial performance is likely to be greatest on operations that specialize in the target commodities.

Spatial variation in the impact of GE crop adoption was examined using the ERS farm resource regions (see box 1). Because pest infestations differ across the U.S., one would expect that the impacts of pest control measures such as GE crops to be greatest where target pest pressures are most severe. Research suggests that the value of Bt corn relative to conventional varieties increases as one moves from east to west in the Corn Belt, because ECB infestations are much more frequent and severe in the western Corn Belt (Hyde et al., 2000). Also, weed pressure tends to be greatest in the Eastern and Southern U.S. because of the hot, moist climate and the longer growing season. Therefore, the expected value of herbicide-tolerant crops would be greater in these areas because of higher conventional weed control costs. The farm resource regions are used to reflect agro-climatic variation across the U.S. and the differences in pest pressures this creates. One change to the regional delineation is that the Heartland is divided along the Mississippi River into the East Heartland and the West Heartland (see box 1). This change better reflects the difference in weed and ECB pressure between these areas.

Variable Specification and Estimation. The adoption-decision model was estimated by a probit analysis of GE crop adoption for each of the corn and soybean farm populations (i.e. all growers and specialized operations). Separate models were estimated for (1) herbicide-tolerant corn, (2) Bt corn, and (3) herbicide-tolerant soybeans. The models were specified using variables that have shown to be related to technology choice in the previous literature (Feder, Just, and Zilberman 1985; Feder and Umali, 1993). Variables regressed against the decision to adopt each technology included operator education, age, primary occupation, risk preference, management level, farm size, specialization in the target commodity, and land tenure (appendix table 3.1). Operator preference toward risk was specified using a risk index constructed according to farmers' answers to a series of survey questions about how they react toward risk, including the use of risk management tools (Bard and Barry, 1998). The operator's management level was specified as higher if the operator reported the use of budgeting or other recordkeeping methods to manage cash flows or control costs. Variables for geographic location were also included in the model to account for the impact that differences in soil, climate, production practices, and pest pressures would have on adoption.

The adoption-impact model was next estimated for each of the farm populations by regressing the same set of explanatory variables, plus other information obtained from the decision model, on alternative measures of farm financial performance. Several measures of farm financial performance were examined, but results are reported for only two measures, modified net farm income (MNFI) per tillable acre, and crop operating margin (RACS) per tillable acre. MNFI and RACS were measured as:

MNFI = Net Farm Income (NFI) + Interest Expense, where:

NFI = Gross Farm Income - Total Farm Operating Expenses (excluding marketing expenses),

Gross Farm Income = Gross Cash Farm Income + Net Change in Inventory Values + Value of Farm Consumption + Imputed Rental Value of Operators Dwelling,

Total Farm Operating Expenses = Total Cash Operating Expenses + Estimated Non-Cash Expense for Paid Labor + Depreciation on Farm Assets; and:

RACS = Gross Value of Crop production – Total Farm Chemical and Seed Expenses,

where gross value of crop production is the production of each crop commodity produced on the farm operation valued at the State-average price received by farmers (USDA, NASS, 1999a). To ascertain the impact of GE crop adoption on financial performance, the predicted probabilities of adoption estimated from the adoption-decision model were also included in the adoption-impact model. Because technology adoption and farm financial performance are jointly determined, the predicted probability of adoption for each technology provided an instrument for the adoption decision that mitigates bias due to simultaneity concerns (Zepeda, 1994). The predicted probabilities were also specified as interaction terms with the geographic location variables. These interaction terms provided a means by which regional differences in the financial impact of adoption could be evaluated. A hypothesis is that regions with greater pest pressures would benefit more from GE crops than other regions. Selectivity variables for each technology were also estimated and added to the adoption-impact model to allow for unbiased and consistent parameter estimates (Lee, 1983). Heckman's two-step procedure (1976) was used to estimate the two-equation model, using weighted regression procedures and a jackknife variance estimator (Dubman, 2000).

Results. Probit parameter estimates for the herbicide-tolerant and the Bt corn adoption-decision models are presented in appendix table 3.2, while parameter estimates for the herbicide-tolerant soybean adoption-decision models are shown in appendix table 3.3. The overall fit of the models was better, as indicated by the higher log-likelihood values (less negative), for the population of specialized corn and soybean producers than it was for all producers of each crop.

The adoption of herbicide-tolerant corn among all corn growers was significantly influenced by many operator characteristics, including age, education, and farm occupation (appendix table 3.2). Greater education, higher age, and having farming as a major occupation were associated with a higher likelihood of adopting herbicide-tolerant corn. These results are consistent with adoption literature, except that older farm operators generally have a lower likelihood of adopting new technologies. The adoption of herbicide-tolerant corn was also more likely among growers in the Western Heartland region relative to those in the Eastern Heartland (the deleted group). However, when the population was restricted to specialized corn operations, the only significant factor was a higher probability of adopting herbicide-tolerant corn in the Northern Crescent region.

Operator characteristics were less important in explaining the adoption of Bt corn, but farm size, specialization, operator risk perception, and region were significant (appendix table 3.2). The likelihood of adopting Bt corn increased (at a decreasing rate) as farm acreage increased. This relationship between farm size and technology adoption is consistent with most adoption literature. Also, increasing a farm's specialization in corn production increased its likelihood of adopting Bt corn. Coefficients on the risk perception variable indicate that more risk-adverse producers were more likely to adopt the Bt technology. While this result is counter to the common profile of technology adopters as more risk taking, the more risk-adverse producers may be attracted to the Bt corn technology because of the insurance it offers against the threat of ECB infestations. Producers in the Western Heartland region were also found to be more likely to adopt Bt corn than were producers in the Eastern Heartland. This result was expected due to higher rates of ECB infestations in portions of the Western Heartland.

In contrast to corn, very few of the variables in either the model for all soybean growers or the model for specialized soybean growers were significant (appendix table 3.3). A possible reason for this lack of explanatory power is the significant diffusion of this technology across the population. Farm adoption rates for herbicide-tolerant soybeans in this study, 37 percent of all soybean farms and 35 percent of specialized soybean farms, were significantly greater than for the other technologies. Thus, the adoption of herbicide-tolerant soybeans has progressed past innovator and early adopter stages into the realm where adopting farmers are much more like the majority of farmers (Rogers, 1995).

Parameter estimates for the adoption-impact models for corn are presented in appendix table 3.2, while those for soybeans are shown in appendix table 3.3. The overall model fit was very poor for both corn and soybean populations that included all producers, with an R-squared ranging from 0.03 to 0.10 among these models. Goodness of fit improved among the specialized corn and soybean populations, but was substantially lower for MNFI than for RACS. This result was not surprising since MNFI accounted for the costs and returns of all farm enterprises, while RACS included only crop returns and the costs that would be most impacted by the adoption of GE crops. Overall, the model fit was best for the RACS model estimated on the populations of specialized corn farms and specialized soybean farms (R-squared of 0.36 and 0.33, respectively).

Nearly all of the explanatory variables were insignificant in both adoption-impact models estimated on the population of all corn producers, and on the model using MNFI among specialized corn producers (appendix table 3.2). The impact of GE crop adoption was not significantly different from zero in any of these models. However, several factors, including GE crop adoption, were found to affect RACS on specialized corn farms. RACS increased with size of operation (at a decreasing rate), increased with operator age, and was higher for producers who more actively managed risk. Farm location was significant, and indicated that the RACS was lower among specialized corn farms in regions outside of the Heartland.

The impact of GE crops on the RACS of specialized corn farms varied by region. To illustrate the impacts, elasticities were estimated to show the percentage change in RACS from a change in the probability of adoption. The elasticity of 0.27 for the adoption of herbicide-tolerant corn on all specialized corn farms indicates that as the probability of adoption increases by 10 percent, RACS increases 2.7 percent. The greatest impact of the adoption of herbicide-tolerant corn was in the Eastern Heartland, where a 10-percent increase in the probability adoption increases RACS by 4.1 percent, significantly greater than in most other regions. This result was not unexpected due to relatively high weed pressures in the East. In contrast to herbicide-tolerant corn, the adoption of Bt corn resulted in a decrease in RACS among the specialized corn farms. The overall elasticity of -0.34 suggests that as the probability of adoption increases 10 percent, RACS declines by 3.4 percent. The negative impact of adoption was significantly less in the Western Heartland compared with the Eastern Heartland (-0.46 versus -0.27), as expected, because of greater pressure by the ECB in portions of the Western Heartland.

Very few explanatory variables were significant in the adoption-impact models for soybeans (appendix table 3.3). The most notable result for soybeans was that the adoption of herbicide-tolerant soybeans had a significant and negative impact on MNFI. This result varied little by region, except that among specialized soybean farms, adoption resulted in a lower MNFI in the Mississippi Portal region than in the Eastern Heartland.

Appendix table 3.1—Means and definitions of variables, financial impact model, 1998

Variables	Definition	Corn (at least one harvested acre)	Corn (specialized operations)	Soybean (at least one harvested acre)	Soybean (specialized operations)
EDYEARS	Education of farm operator (years)	12.99	13.42	13.03	12.77
OPAGE	Age of farm operator (years)	51	50	50	50
OCCUPF	Occupation of farm operator (1= farming; 0 otherwise)	0.68	0.55	0.65	0.42
SIZE	Farm size, measured as total harvested acres (100 acres)	4.44	4.47	4.82	2.94
SIZESQ	Farm size, squared	59.25	54.06	65.64	31.08
SPECIALIZ	Value of sales of relevant commodity / Total value of sales	0.30	—	0.40	—
RISKPERCP	Operator's risk perception (index:10=least, 50=most risk taking)	28.37	27.83	28.62	30.79
BUDGET	Operator's management level (`= use budgeting or other record keeping to manage cash flow and/or control cost; 0 otherwise)	0.74	0.76	0.72	0.55
TENURE	Rented acres / Total operated acres	0.61	0.61	0.55	0.61
HRTLNDW	Farm location (1= West Heartland; 0 otherwise)	0.30	0.42	0.31	0.23
NCRESCNT	Farm location (1= Northern crescent; 0 otherwise)	0.24	0.12	0.15	0.14
PRGATEWY	Farm location (1= Prairie Gateway; 0 otherwise)	0.07	0.06	—	—
MISSPORT	Farm location (1= Mississippi Portal; 0 otherwise)	—	—	0.04	0.06
OTHREGN[1]	Farm location (1= other crop producing region; 0 otherwise)	0.15	0.06	0.15	0.08
MNFI	Modified net farm income per tillable acre ($)	101.47	82.23	99.07	65.40
RACS	Crop value less cost of chemicals and seed per tillable acre ($)	163.87	206.48	170.38	162.71
ADOPT_HT	Herbicide-tolerant seed (1= adoption; 0 otherwise)	0.05	0.06	0.37	0.35
ADOPT_Bt	Bt seed (1= adoption; 0 otherwise)	0.20	0.30	—	—
Sample size		2,719	535	2,321	395
Population		460,210	118,158	400,542	112,975

Note: *ADOPT_HT*=1 and *ADOPT_Bt*=1 include a small fraction of farms that used stacked=trait seeds.

[1] *OTHREGN* in the case of corn includes Northern Great Plains, Eastern Upland, Southern Seaboard, Fruitful Rim, and Basin and Range regions, and in the case of soybeans includes Northern Great Plains, Prairie Gateway, Eastern Upland, Southern Seaboard, Fruitful Rim, and Basin and Range regions.

— = Not applicable

Appendix table 3.2—Regression estimates of the financial impact model in corn production, 1998

	Corn (at least 1 harvested acre)		Corn (specialized operations)	
Variables	*MNFI*[1]	*RACS*[2]	*MNFI*[1]	*RACS*[2]
INTERCEPT	285.87	146.07	47.04	372.58***
EDYEARS	5.17	-21.55	10.50	0.10
OPAGE	-1.25	1.56	2.31	1.05***
OCCUPF	52.38*	-4.40	-14.15	-21.29
SIZE	-1.53	-12.23	6.01	4.76***
SIZESQ	0.06	0.18	-0.07	-0.05***
SPECIALIZ	-33.90	56.42	—	—
RISKPERCP	-5.77	1.87	-6.49	-7.69***
BUDGET	8.90	51.55	8.91	26.46
HRTLNDW	117.63	-62.78	49.73	17.69
NCRESCNT	18.27	97.42	31.21	-99.97***
PRGATEWY	138.03	-25.51	-18.59	-108.72***
OTHREGN[3]	25.53	24.21	216.55	-96.97***
PHT[4]	-655.40	961.73	126.73	1402.03***
PBt[5]	-309.58	840.17	-345.66	-319.70***
*PHT*HRTLNDW*	100.67	-504.50	-114.24	-731.63***
*PHT*NCRESCNT*	-1215.14	1660.49	-1144.22	-812.51**
*PHT*PRGATEWY*	128.54	-1413.79	352.02	-325.27
*PHT*OTHRREGN*	-1425.66	30.13	-212.97	-746.41*
*PBt*HRTLNDW*	-50.94	-290.62	36.53	131.65*
*PBt*NCRESCNT*	436.13	-1265.58	402.22	155.08
*PBt*PRGATEWY*	-361.46	120.11	-27.54	97.76
*PBt*OTHREGN*	375.03	-135.87	-900.09*	-15.29
LAMBDAHT	-9.59	0.19	-3.99	3.47
LAMBDABt	6.09	3.92	-0.98	16.31***
R^2	0.02	0.003	0.07	0.36
Sample size	2,719		535	
Population	460,210		118,158	

[1] *MNFI* denotes modified net farm income per tillable acre.

[2] *RACS* denotes returns above cost of chemicals and seed per tillable acre.

[3] *OTHREGN* includes Northern Great Plains, Eastern Uplands, Southern Seaboard, Fruitful Rim, and Basin and Range regions.

[4] *PHT* is the predicted probability of adopting herbicide-tolerant corn estimated from the adoption-decision model.

[5] *PBt* is the predicted probability of adopting Bt corn estimated from the adoption-decision model.

* Significant at 10 percent. ** Significant at 5 percent. *** Significant at 1 percent.

— = Not applicable.

Appendix table 3.3— Regression estimates of the financial impact model in soybean production, 1998

Variables	Soybean (at least 1 harvested acre)		Soybean (specialized operations)	
	MNFI[1]	*RACS*[2]	*MNFI*[1]	*RACS*[2]
INTERCEPT	789.19***	158.26**	506.15***	302.85**
EDYEARS	20.14	3.82	-3.58	-1.64
OPAGE	-0.88	-0.13	-0.08	-1.09**
OCCUPF	35.30	-8.85	60.79**	31.24
SIZE	0.72	3.31	-3.98	-1.66
SIZESQ	-0.02	-0.04	0.08	0.04
SPECIALIZ	-61.01	38.20	—	—
RISKPERCP	-17.37**	*2.88	-9.78***	-2.45
BUDGET	-17.10	6.07	-44.19*	-16.04
HRTLNDW	135.76	25.40	-31.26	4.28
NCRESCNT	-142.56	-34.10	53.07	18.72
MISSPORT	302.94	67.21	100.30	-82.94***
OTHREGN[3]	-145.95	48.41	-156.67	-59.34*
PHT[4]	-1029.13**	118.60	-237.00***	67.54
*PHT*HRTLNDW*	-203.92	-108.73	100.10	-27.15
*PHT*NCRESCNT*	158.07	-31.68	-68.15	-64.77
*PHT*MISSPORT*	-687.93	-214.74	-410.68**	7.25
*PHT*OTHRREGN*	93.24	-263.77	226.29	-35.52
LAMBDAHT	2.59	2.73	-15.76	8.83
R^2	0.02	0.003	0.07	0.36
Sample size	2,321		395	
Population	400,542		112,975	

[1] *MNFI* denotes modified net farm income per tillable acre.

[2] *RACS* denotes returns above cost of chemicals and seed per tillable acre.

[3] *OTHREGN* includes Northern Great Plains, Prairie Gateway, Eastern Upland, Southern Seaboard, Fruitful Rim, and Basin and Range regions.

[4] *PHT* is the predicted probability of adopting herbicide-tolerant soybeans estimated from the adoption-decision model.

* Significant at 10 percent. ** Significant at 5 percent. *** Significant at 1 percent.

— = Not applicable.

Appendix IV. A Simultaneous Adoption Model for Herbicide-Tolerant Soybeans and No-Till

This appendix presents an econometric model developed to address the question of whether the availability of herbicide-tolerant soybeans is encouraging farmers to adopt no-till practices for soybean production (Soule and Klotz-Ingram, 2000). Because the availability of herbicide-tolerant soybeans may affect the no-till decision, while at the same time, the use of no-till may impact the decision to adopt herbicide-tolerant seeds, the two decisions must be considered simultaneously. Therefore, a simultaneous, two-equation econometric model is developed, where both equations are binary, to address the simultaneous nature of the decisions. The model is used to determine which factors are most important in explaining the adoption of no-till and herbicide-tolerant soybeans. Also, the hypothesis of simultaneity is tested to determine if the two decisions are actually endogenous to each other.

Model Specification and Testing. Studies of the adoption of agricultural technologies usually motivate the binomial or multinomial variable approach using either a latent variable or random utility argument. In the latent variable case (Long, 1997), there is an unobserved latent variable (y*), such as expected profits or expected utility from each technology choice, that generates the observed binary variable of actual technology choice. The latent variable is assumed to be linearly related to the observed explanatory variables through a structural model of the form:

$$y_i^* = \delta'\mathbf{X_i} + e_i , \quad (i = 1, ..., N) \qquad (1)$$

The latent variable is then linked to the observed binary variable through the following equation:

$$\begin{aligned} y_i &= 1 \text{ if } y_i^* > 0 , \\ y_i &= 0 \text{ if } y_i^* \leq 0 . \end{aligned} \qquad (2)$$

The random utility model is based on the idea that the farmer chooses the technology (y_i=1) that maximizes the utility gained from the choice between technologies. In either case, the argument results, generally, in a model of the form:

$$Pr[y_i = 1] = F(\delta'\mathbf{X_i}) , \qquad (3)$$

where Pr[.] is a probability function and $F(.)$ is the cumulative distribution function, and $\mathbf{X_i}$ is a vector of variables explaining the probability of adoption. The exact distribution of F depends on the distribution of the random term e_i. If e_i is distributed as a normal random variable, then we have a probit statistical model.

In this study, the single-equation probit model is extended to a simultaneous model with two probit equations using a two-stage method. Following Maddala (1983, p. 246), two reduced-form probit models are first estimated:

$$\begin{aligned} y_1^* &= \delta_1'\mathbf{X} + e_1 \\ y_2^* &= \delta_2'\mathbf{X} + e_2 \end{aligned} \qquad (4)$$

where $\mathbf{X}$ includes all exogenous variables expected to impact the probability of adoption of either technology. Next, the structural equations below, which also include predicted values of y_1^{**} and y_2^{**}, retrieved from equation (4), are estimated, where X_1 and X_2 are the explanatory variables expected to impact each technology:

$$\begin{aligned} y_1^{**} &= \Upsilon_1 \; y_2^{**} + \delta_1'\mathbf{X_1} + u_1 \\ y_2^{**} &= \Upsilon_2 \; y_1^{**} + \delta_2'\mathbf{X_2} + u_2 \end{aligned} \qquad (5)$$

In the empirical analysis, the simultaneous system presented above is estimated first. Then, two standard, single-equation probit models for the probability of adopting no-till and herbicide-tolerant seeds are estimated separately to test the simultaneous adoption decision. In each equation, we include the adoption of the other technology as one of the explanatory variables. The parameters from the two models are then used to construct Wu-Hausman tests to determine the simultaneity of the two decisions. The Wu-Hausman statistic tests the null hypothesis that the standard probit model that ignores simultaneity is the correct specification. If the conservation tillage and herbicide-tolerant seed choices are indeed simultaneous, the standard probit estimates are inconsistent and the simultaneous equation model is preferred.

Data and Estimation. Data come from the 1997 ARMS survey. Explanatory variables included in both the no-till and herbicide-tolerant seed equations are regional dummy variables, operator's education and age, dummy variables for whether the operator worked off-farm for more than 200 days per year, rotated soybeans with other crops, irrigated, or kept records to track pests (appendix table 4.1). In addition, the no-till equation included the following explanatory variables: whether the operator participated in government programs, the proportion of the farm in corn and soybeans, average precipitation, whether the field is cash-rented or share-rented (vs. owned) by the operator, and whether the field has been classified as highly erodible by the National Resources Conservation Service (NRCS). Additional variables in the herbicide-tolerant seed equation are whether the farm is mainly a crop (vs. livestock) farm, the yield the farmer normally expects on the field, and whether the operator used herbicide-tolerant seeds in 1996.

Results. Farm size was positively related to the adoption of no-till, but was not related to herbicide-tolerant soybean adoption (appendix table 4.2). Farmer age and education level, the number of days the operator worked off-farm, and whether or not farmers irrigated or cultivated continuous soybeans did not significantly affect the adoption of no-till or herbicide-tolerant seed. Farmers who kept records to track weeds or other pests were more likely to use no-till practices. However, recordkeeping was not associated with the adoption of herbicide-tolerant seed.

There are several variables unique to either the no-till or the herbicide-tolerant seed model that were significant. In the no-till model, farmers who received government program payments and farmers with highly erodible land (HEL) were more likely to use no-till. This is probably because farmers need to meet conservation compliance requirements on HEL in order to receive program payments. Farmers who experienced greater precipitation levels were also more likely to use no-till practices, probably to protect soil from eroding. Furthermore, farmers having a greater proportion of their farm devoted to corn or soybeans (generally considered to be more erosive crops) had a higher probability of adopting no-till, and farmers who share-rented were less likely to use no-till than owner-operators.

In reference to the herbicide-tolerant seed model results, crop farmers were less likely to use these seeds than livestock farmers. Other positive and significant variables included expected yields (indicating that higher expected yields may increase the expected value of adopting the technology) and whether a farmer used herbicide-tolerant seed the previous year.

The most interesting result in the simultaneous model was the interactive effects of the no-till and herbicide-tolerant seed variables. Farmers using no-till were found to have a higher probability of adopting herbicide-tolerant seed, but using herbicide-tolerant seed did not significantly affect no-till adoption. The result seems to suggest that farmers already using no-till found herbicide-tolerant seeds to be an effective weed control mechanism that could be easily incorporated into their weed management systems. Alternatively, the commercialization of herbicide-tolerant soybeans did not seem to encourage the adoption of no-till, at least at the time of the survey in 1997. However, this may change as herbicide-tolerant soybeans gain greater acceptance.

Two standard models were evaluated and compared to the simultaneous model with the Wu-Hausman statistic. For the single-equation no-till model, herbicide-tolerant seed adoption was found to be a significant explanatory factor, contrary to the simultaneous model. For both the single-equation and simultaneous-equation models, no-till was a significant explanatory factor in herbicide-tolerant seed adoption. Two Wu-Hausman statistics were calculated to test the null hypotheses that two standard probit models, rather than the simultaneous equations, is the correct specification. For the no-till model, the χ^2 statistic is 12.8, meaning we reject the null hypothesis that the standard model is the correct specification. However, for the herbicide-tolerant seed model, we cannot reject the null hypothesis (χ^2 statistic of 0.6). This suggests that accounting for simultaneity is important for the no-till decision but not for the seed-use decision. This result serves to strengthen our finding that the adoption of conservation tillage, at least in 1997, was not affected by the introduction of herbicide-tolerant seeds. In addition, not incorporating the simultaneity of the decision into the modeling effort could lead researchers to erroneously conclude that availability of herbicide-tolerant soybeans is driving no-till adoption, as suggested by the standard model, when this is not the case. Variables that were significant in the simultaneous no-till model but not in the standard model include farm size and the proportion of the farm in corn and soybeans. On the other hand, no-till adoption was found to have a significant impact on herbicide-tolerant seed adoption in both the standard model and simultaneous model, so the misspecification does not lead to incorrect conclusions on the main variable of interest. For herbicide-tolerant seeds, the standard probit and the simultaneous probit results are very similar, the main difference being that off-farm work, recordkeeping, and irrigation were found to be significant in the standard model while they were not in the simultaneous equation model.

The results suggest that farmers already using no-till are more likely to adopt herbicide-tolerant seeds, but the use of herbicide-tolerant seeds is not an important factor affecting no-till adoption. However, the results should be taken with caution since the conclusion is based on 1997 data when herbicide-tolerant seeds were still a new technology, and we may start seeing an impact of herbicide-tolerant seed adoption on no-till adoption in the future.

Inconsistent estimates provided by estimating two single-equation probit models separately imply that herbicide-tolerant seed adoption is a significant factor in no-till adoption. However, the consistent estimates provided by the simultaneous equation approach suggest that this is not the case and show the importance of considering simultaneity when modeling adoption decisions that are known to be interrelated.

Appendix table 4.1—Definitions of variables–Adoption of no-till and herbicide-tolerant soybeans, 1997

Variable	Description
Lakes	1 if in MI, MN, or WI
Corn Belt	1 if in IL, IN, IO, MS, or OH
Southeast	1 if in KY, NC, or TN
Plains	1 if in KS, NE, or SD
Delta	1 if in AR, LA, or MS
Farm size	farm size in 100s of acres
Age	age of the operator, years
Education	1 if operator has some college education
Off-farm work	1 if operator works off-farm 200 days or more per year
No rotation	1 if no rotation of crop (continuous soybeans)
Irrigation	1 if the field is irrigated
Records	1 if records were kept to track pests, including weeds
Program participant	1 if operator received some Government payments in 1997
HEL	1 if field is classified as Highly Erodible by NRCS
Avg. precipitation	30-year average annual precipitation, in centimeters
Corn-soy prop.	Fraction of farm planted to corn and soybeans
Cash-rent	1 if field is cash-rented
Share-rent	1 if field is share-rented
Crop farm	1 if the farm is primarily a crop rather than a livestock operation
Expected yield	yield per acre (in bushels) that operator normally expects
Herb. tolerant seed, 1997	1 if used herbicide-tolerant soybeans in 1997
Herb. tolerant seed, 1996	1 if used herbicide-tolerant soybeans in 1996
No-till	1 if used no-till in 1997

Appendix table 4.2—Simultaneous-equation model of no-till and herbicide-tolerant soybean adoption, U.S. 1997

	No-till		Herbicide-tolerant soybeans	
Variables	parameter estimate	t-ratio	parameter estimate	t-ratio
Constant	-3.694	-4.824**	-1.053	-2.231**
Lakes	0.797	2.873**	-1.238	-3.395**
Corn Belt	1.053	4.496**	-1.198	-3.695**
Southeast	1.088	5.960**	-1.000	-3.000**
Plains	0.964	3.902**	-0.800	-3.117**
Farm size	0.015	2.256**	0.005	0.450
Age	-0.006	-1.366	0.003	0.417
Education	0.200	1.519	0.182	1.596
Off-farm work	-0.021	-0.174	0.264	1.602
No rotation	-0.234	-0.793	-0.022	-0.080
Irrigation	-0.329	-1.084	-0.338	-1.175
Records	0.449	2.606**	0.226	0.984
Program participant	0.373	2.370**		
HEL	0.578	3.689**		
Avg. precipitation	0.013	2.940**		
Corn-soy prop.	0.005	2.030*		
Cash-rent	0.195	1.662		
Share-rent	-0.300	-2.281**		
Crop farm			-0.320	-2.153**
Expected yield			0.030	3.336**
Herb. tolerant seed, 1996			3.028	3.379**
Herb. tolerant seed, 1997	-0.097	-0.604		
No-till			0.659	2.394**
% correct predictions	75		87	

** Significant at 5-percent level, cutoff is 2.145 for 14 degrees of freedom.
* Significant at 10-percent level, cutoff is 1.761 for 14 degrees of freedom.