Chapter 3.3

Biotechnology and Agriculture

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Farmers adopting first-generation genetically engineered (GE) crops derive tangible benefits, even though not all benefits are reflected in standard measures of net returns. The impacts of GE crops vary with annual pest infestations, seed premiums, prices of alternative pest control programs, and any premiums paid for segregated (i.e., non-GE) crops.

Introduction

The unprecedented growth in crop yields and agricultural productivity over the 20th century owes much to a series of biological innovations embodied in seeds, beginning with the development of hybrid crops in the United States in the early part of the century and continuing with high-yielding varieties during the Green Revolution of the 1960s and 1970s. More recently, developments in modern biotechnology are expanding the processes of biological innovations by providing new tools. Agricultural biotechnology is a collection of scientific techniques, including genetic engineering, that are used to create, improve, or modify plants, animals, and microorganisms. Genetic engineering (GE) techniques allow a more precise and time-saving alteration of a plant's traits (facilitating the development of characteristics not possible through traditional plant breeding), and permit targeting of a single plant trait (decreasing the number of unintended characteristics that may occur with traditional breeding). Despite the benefits, however, environmental and consumer concerns currently limit acceptance of agricultural biotechnology, particularly in Europe. The ultimate contributions of agricultural biotechnology will depend on our ability to recognize its potential benefits and its risks (Fernandez-Cornejo at al., 1999).

Despite a focus here on genetically engineered crops in agriculture, the future importance of genetically engineered animals should not be understated. As a National Research Council (NRC) report indicates, the increased demand for meat and deterioration and loss of agricultural land will lead to pressures to exploit biotechnology to improve productivity in animal agriculture.

GE crops are often classified into one of three generations (Panos, 1998). First-generation crops have enhanced input traits, such as herbicide tolerance, insect resistance, and resistance to environmental stresses like drought. Second-generation crops have added-value output traits, such as nutrient-enhanced seeds for feed. Third-generation crops produce pharmaceuticals, bio-based fuels, and products beyond traditional food and fiber (table 3.1.1). At present, GE crops widely adopted are first-generation.

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Table 3.3.1
Biotech crops currently available and in development ("in the pipeline") in the U.S.

Crop	Input traits				Product quality[11]	Other[13]
	Herbicide tolerance	Insect resistance	Virus/fungus resistance	Agronomic properties[9]		
Corn	C	C[5]	D	D	D	D
Soybeans	C	D	--	D	D	--
Cotton	C	C[6]	--	D	D	--
Potatoes		C[7]	D	D	D	D
Wheat	C[2]	--	D	--	--	--
Other field crops[1]	C[3] D[4]	D	D	D	D	D
Tomato, squash, melon	--	--	D	D	C[12] D	D
Other vegetables	D	--	--	--	D	--
Papaya	--	--	C[8]	--	--	--
Fruit trees	--	--	D	--	D	--
Other trees, flowers	--	--	--	D[10]	D	--

C = Currently available; D = In various stages of development.
[1]Includes barley, canola, peanuts, tobacco, rice, alfalfa, etc.
[2]Monsanto discontinued breeding and field-level research on its Roundup Ready wheat in 2004, deferring all further efforts to introduce it.
[3]Canola.
[4]Barley, rice, sugarbeets.
[5]Bt corn to control the corn borer commercially available since 1996; Bt corn for corn rootworm control commercially available since 2003.
[6]Bt cotton to control the tobacco budworm, the bollworm, and the pink bollworm commercially available since 1996.
[7]Bt potatoes resistant to the Colorado potato beetle commercially introduced in 1996. They were withdrawn from the market in 1999.
[8]Researchers at Cornell University and at the University of Hawaii developed two virus-resistant varieties of GE papaya. First commercial plantings were made in 1998. They were successful and were planted on more than 30 percent of Hawaii's papaya acreage in 1999.
[9]Resistance to cold, drought, frost, salinity; more efficient use of nitrogen; increased yield.
[10]Modified lignin content.
[11]Includes delayed ripening (fruits and vegetables with longer shelf life); increased protein, carbohydrate, and oil content; improved fiber properties (cotton), gluten content (wheat), naturally decaffeinated (coffee).
[12]Tomato genetically engineered to remain on the vine longer and ripen to full flavor after harvest was withdrawn from the market.
[13]Includes nutraceuticals, pharmaceuticals, and industrial products, such as increased vitamin, iron, beta-carotene (antioxidant), lycopene (anti-cancer), amino acid content; antibodies; vaccines; and specialty machine oils.

Sources: Virginia Polytechnic Institute and State University; USDA, APHIS; Colorado State; Shoemaker et al.; Pew.

Seed Industry

Until the 1930s, most commercial seed suppliers were small, family-owned businesses lacking the financial resources to pursue their own research and development. These small businesses depended almost exclusively on plant breeding research in the public sector. The development and rapid producer acceptance of hybrid corn and greater legal protection of intellectual property rights brought large-scale change to the seed industry, particularly rapid increases in private R&D and market concentration in the U.S. seed industry.

Private R&D expenditures on plant breeding increased 1,300 percent between 1960 and 1996 (adjusted for inflation), while real public R&D expenditures changed little (Fernandez-Cornejo, 2004a, fig. 14). Two principal forms of legal protection behind the growth in private R&D on crop varieties are plant variety protection (PVP) certificates issued by the Plant Variety Protection Office of the USDA and patents issued by the U.S. Patent and Trademark Office of the U.S. Department of Commerce. Ag biotech patents, mostly dealing with some aspect of plant breeding, have outpaced the general upward trend in patenting throughout the U.S. economy. During 1996-2000, 75 percent of over 4,200 new agricultural biotechnology patents went to private industry. As private R&D on plant breeding grew rapidly, market concentration also increased. For example, the four largest corn seed firms accounted for nearly 70 percent of U.S. corn seed sales in 1997, and the four largest cotton seed firms provided more than 90 percent of the cotton seed varieties planted (Fernandez-Cornejo, 2004a, pp. 30-37). For more on R&D, see Chapter 3.2, "Agricultural Research and Development."

Biotech R&D

The creation of new plant varieties with useful agronomic properties requires significant knowledge of traditional plant breeding. Moreover, the commercial success of GE crop varieties typically requires that biotechnology-derived trait enhancements be incorporated into successful cultivars. In this sense, plant breeding and biotechnology are complementary. Acquisition of firms with established varieties by companies with the ability to improve varieties using biotechnology is one possible rationale for recent consolidation in the U.S. seed industry.

The number of field releases of plant varieties for testing purposes provides a useful indicator of R&D efforts on GE crops. The release of GE varieties of organisms into the environment is regulated and monitored by USDA's Animal and Plant Health Inspection Service (APHIS). Private companies and public institutions proposing tests of such organisms in the environment either notify APHIS of their intent or submit an application for a field release permit (referred to here as an application). If an APHIS review of the application (notification or permit application) establishes that there are no significant environmental risks associated with a release, a notification is acknowledged or a field permit is issued (referred to here as an "approval").

The number of applications received by APHIS for GE plant varieties increased from 9 in 1987 to a high of 1,206 in 1998. By mid-February 2005, nearly 11,300 applications had been received and more than 10,400 (92 percent) had been approved (VT, 2005). Most applications approved for field testing involved major crops such as corn (over 4,800 applications), soybeans (797), potatoes (745), and cotton (708). Applications approved between 1987 and mid-February 2005 included GE varieties with herbicide tolerance (3,774), insect resistance (3,083), improved product quality (flavor, appearance, or nutrition) (2,241), virus resistance (1,238), agronomic properties like drought resistance (978), and fungal resistance (639).

After extensively field testing a GE variety, an applicant may petition USDA to deregulate (grant permission to produce and sell) the product. If, after extensive review, USDA determines that the new variety poses no significant risk to agriculture or the environment, permission is granted. As of February 2005, USDA had received 103 petitions and granted 63 (including 17 for corn, 11 for tomato, 9 for cotton, 5 for soybeans, and 5 for potatoes). Thirty-six percent of the released varieties have herbicide-tolerance traits, 27 percent have insect-resistance traits, and 17 percent have product-quality traits (VT, 2005).

Extent of Adoption of GE Crops

Driven by farmers' expectations of higher yields, savings in management time, and lower pesticide costs, the rate at which farmers adopt GE crop varieties has risen steadily despite consumer resistance in some countries. An estimated 200 million acres of GE crops with herbicide tolerance and/or insect resistance were cultivated in 17 countries worldwide in 2004, a 20-percent increase over 2003, and U.S. acreage accounts for 59 percent of this amount (Argentina for 20 percent, Canada and Brazil 6 percent each, and China 5 percent) (ISAAA, 2004).

GE varieties of soybeans, corn, and cotton have been available commercially in the U.S. since 1996. Since then, their rate of use by U.S. farmers has climbed most years (fig. 3.3.1).

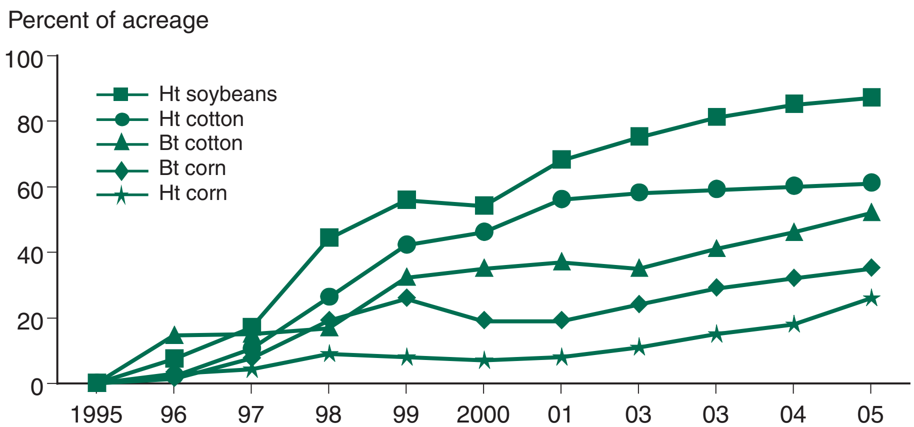
For the most part, farmers have adopted herbicide-tolerant (HT) varieties, which help control weeds, faster than insect-resistant varieties.

Weeds are such a pervasive pest for soybeans, corn, and cotton that over 90 percent of planted acreage for each crop was treated with herbicides in recent years. Acreage share for HT soybeans has expanded more rapidly than that for HT varieties of cotton and corn, reaching 87 percent of U.S. soybean acreage in 2005. Farmers' adoption of HT soybeans has been widespread among major growing States, ranging in 2005 from 76 percent in Michigan to 95 percent in South Dakota. Acreage share for HT cotton has also expanded rapidly, reaching 61 percent in 2005. In contrast, acreage share for HT corn reached only 26 percent in 2005, but this has also trended upward since 2001 (Fernandez-Cornejo, 2004b).

Insect-resistant crops contain a gene from a soil bacterium, *Bacillus thuringiensis* (Bt), which produces a protein toxic to specific insects. Acreage shares for Bt cotton and corn are lower than those for HT soybeans and cotton and vary much more across producing States, with adoption more concentrated in areas with high infestations of targeted pests (insect infestation varies much more widely across locations than does weed infestation). Farmers planted Bt cotton to control tobacco budworm, bollworm, and pink bollworm on 52 percent of cotton acreage in 2005. Acreage share ranged from 13 percent in California to 86 percent in Louisiana. Bt corn,

Figure 3.3.1

Adoption of genetically engineered crops in the U.S.



Data for each crop category include varieties with stacked traits.

Source: ERS elaboration from several USDA surveys.

originally developed to control the European corn borer, was planted on 35 percent of corn acreage in 2005, up from 29 percent in 2003 and 24 percent in 2002. The recent increases in acreage share may be largely due to the commercial introduction in 2003/04 of a new Bt corn variety that is resistant to the corn rootworm, a pest that may be even more destructive to corn yields than the European corn borer.

Other GE crops used by U.S. farmers over the past 10 years include herbicide-tolerant canola, Bt potatoes (introduced by Monsanto in 1996 and withdrawn from the market after the 2001 season), virus-resistant papaya (developed by Cornell University and University of Hawaii and introduced commercially in 1998), and virus-resistant squash (table 3.1.1). In addition, a tomato genetically engineered to remain on the vine longer and ripen to full flavor after harvest was introduced by Calgene in 1994, but withdrawn after being available sporadically for several years (Colorado State University, 2004).

Main Reasons Stated by U.S. Farmers for Adopting GE Crops

According to surveys conducted by USDA in 2001-03, most farmers (59-79 percent) adopting GE corn, cotton, and soybeans indicated that they did so mainly to "increase yields through improved pest control" (fig. 3.3.2). The second most cited aim was to "save management time and make other practices easier" (15 to 26 percent, except for Bt corn, which was much lower); the third reason was to "to decrease pesticide costs" (9-17 percent of adopters). All other reasons combined accounted for 3-7 percent of adopters. Hence, factors expected to increase economic profitability by increasing revenues per acre (yield times price of the crop) or reducing costs (operator labor, pesticides) are expected to promote adoption most.

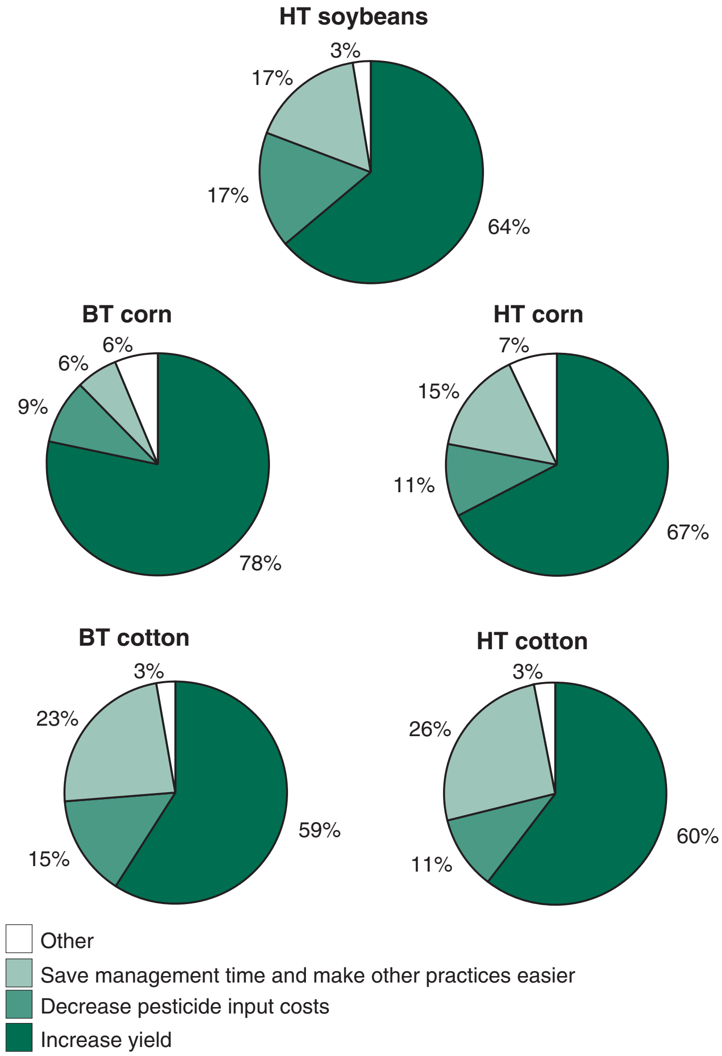
Adoption of GE Crops and Yields

The first generation of GE crops does not increase the yield potential of a hybrid. In fact, yield potential 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 hybrids, particularly when pest infestation occurs. This effect is particularly important in the case of Bt crops. Before the commercial introduction of Bt corn in 1996, the European corn borer was only partially controlled using chemical insecticides. The economics of chemical use was not always favorable, and timely application was difficult. For these reasons, many farmers accepted yield losses rather than incur the expense of chemical pesticides to treat the insect. Consequently, the use of Bt corn often resulted in yield gains rather than pesticide savings. On the other hand, a different Bt corn trait selected for resistance against the corn rootworm, previously controlled using chemical insecticides, may provide substantial insecticide savings. This new Bt corn variety was recently introduced commercially.

An ERS study estimated the impact of adopting GE crops on yields using an adoption model and 1997 survey data (Fernandez-Cornejo and McBride,

Figure 3.3.2

Main reasons for adopting GE crops, according to farmers



Source: 2004 USDA Agricultural Resource Management Survey, Economic Research Service, USDA.

2002, pp. 20-23). The study shows that an increase of 10 percent in the adoption of HT cotton led to a 1.7-percent increase in yields. Similarly, the adoption of Bt cotton in the Southeast was related to a significant increase in yields. On the other hand, the adoption of HT soybeans was related to only small (but still significant) increases in yields.

Adoption, Net Returns, and Household Income

According to an ERS study, the impacts of GE crop adoption on U.S. farmers vary by crop and technology (Fernandez-Cornejo and McBride, 2002, pp. 20-25). The main results of the ERS study are presented below.

- ***Planting HT cotton and corn was associated with increased producer net returns, but HT corn acreage was limited.*** The limited acreage on which herbicide-tolerant corn has been used is likely to be 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. Limited adoption of HT corn may be due to constraints imposed on rotation with soybeans. Also, some HT corn varieties have limited approval outside the U.S., restricting their export market potential.

- ***Adoption of Bt cotton and corn was associated with increased returns when pest pressures were high enough.*** The adoption of Bt cotton had a positive association with producer net returns in 1997, but the association was negative for Bt corn in 1998. This suggests that Bt corn may have been used on some acreage where the value of protection against the European corn borer (ECB) was lower than the premium paid for the Bt seed. Because pest infestations differ across the country, the economic benefits of Bt corn are likely to be greatest where target pest pressures are most severe. The decision to use Bt corn must be made before observing the ECB pest pressure, and damage caused by the ECB varies from year to year. Some farmers may incorrectly forecast infestation levels, corn prices, and yield losses due to infestations, resulting in "overadoption." Also, producers may be willing to pay a premium for Bt corn because it reduces the risk of significant losses if higher-than-expected pest damage does occur.

- ***Despite the rapid adoption of HT soybeans by U.S. farmers, no significant impact on net farm returns was evident in 1997 or 1998.*** This lack of profitability suggests that other factors may be driving adoption for many adopters, such as the simplicity and flexibility (less management time) of weed control. This implies more time available to off-farm employment by farm operators and their spouses. (On average, off-farm earned income is more than twice the net income earned from farming.)

- ***Recent ERS research using 2000 data showed that adoption of HT soybeans was associated with significantly higher off-farm household income for U.S. soybean farmers.*** Onfarm household income was not significantly related to adoption, but total farm household income is significantly higher for adopters.

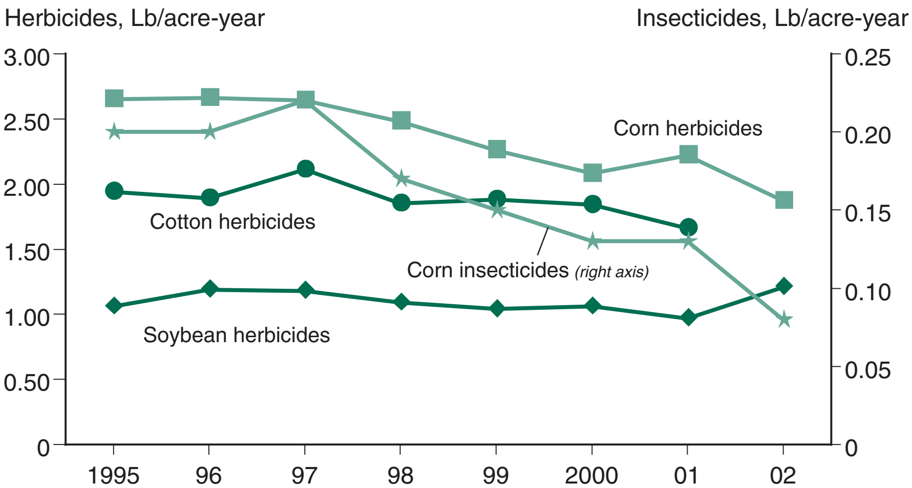
Adoption and Pesticide Use

On the environmental side, pesticide use on corn and soybeans has declined since the introduction of GE corn and soybeans in 1996 (fig. 3.3.3).

In addition, ERS research suggests that, controlling for other factors, pesticide use declined with adoption. The overall reduction in pesticide use associated with the increased adoption of GE crops (Bt cotton; and HT corn, cotton, and soybeans, using 1997/1998 data) also resulted in a significant reduction in potential exposure to pesticides. The decline in pesticide applications was estimated to be 19.1 million acre-treatments (Fernandez-Cornejo and McBride, 2002, pp. 26-28). Total pesticides applied to corn, soybeans, and cotton declined by about 2.5 million pounds (active ingredients), despite the (slight) net increase in the amount of herbicides applied to

Figure 3.3.3

Pesticide use in major field crops



Source: USDA, NASS surveys.

soybeans. For more information on pesticide use, see Chapter 4.3, "Pest Management".

Adoption and Conservation Tillage

The environmental impact of conservation tillage (including no-till, ridge-till, and mulch-till) is well documented. Conservation tillage reduces soil erosion by wind and water, increases water retention, and reduces soil degradation and water/chemical runoff. For more on conservation tillage, see Chapter 4.2, "Soil Management and Conservation".

According to USDA survey data, the portion of acreage planted with HT soybeans under conservation tillage was larger than the portion of acreage growing conventional soybeans. About 60 percent of the area planted with HT soybeans was under conservation tillage in 1997 (fig. 3.3.4), versus 40 percent of conventional soybeans.

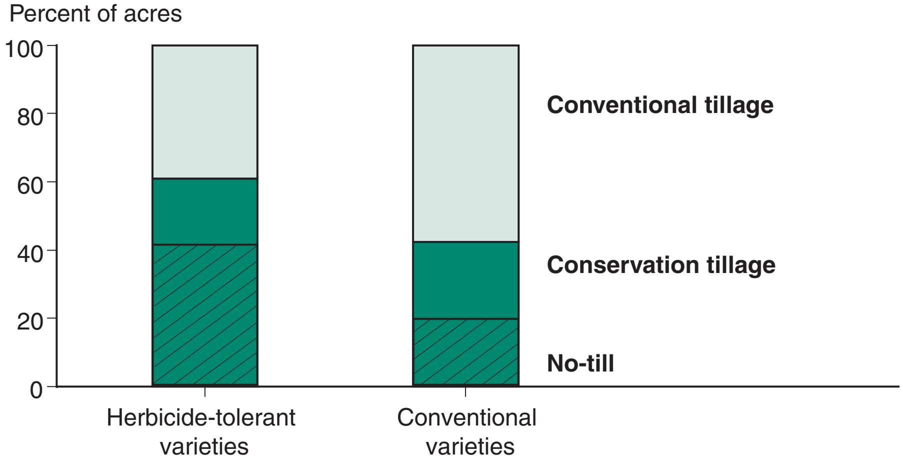
Differences in the use of no-till between adopters and nonadopters of HT soybeans are even more pronounced: 40 percent versus 20 percent. As a result, adoption of HT crops may indirectly benefit the environment by encouraging the adoption of soil conservation practices that control soil erosion, soil degradation, and runoff.

Economic Benefits of GE Crops

GE crops can offer producers distinct advantages over conventional varieties, such as higher yields and lower pest control costs. But producers are not the only ones to gain from the adoption of GE crops. Biotechnology developers and seed companies gain by charging technology fees and seed premiums to adopters of GE varieties. Ultimately, U.S. and foreign consumers may benefit from GE crops through lower commodity prices, which result from increased supplies.

Figure 3.3.4

Soybeans area under conservation tillage and no-till, 1997



Source: Fernandez-Cornejo and McBride (2002).

ERS estimated the total market benefit arising from the adoption of three biotech crops in 1997: herbicide-tolerant soybeans, insect-resistant (Bt) cotton, and herbicide-tolerant cotton. Estimated benefits were around $210 million for Bt cotton, $230 million for HT cotton, and $310 million for HT soybeans (Price et al., 2003). This benefit includes the change in total welfare in both the seed input and commodity output markets. Estimated benefits and their distribution depend particularly on the analytical framework, supply and demand elasticity assumptions, crops considered, and year-specific factors (such as weather).

There are tangible benefits to farmers who adopt first-generation GE crops. Not all of the benefits are reflected in standard measures of net returns. As in all studies, results should be interpreted carefully, especially since the impact studies are based on a few years of data. 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 (i.e., non-GE) crops. These factors will continue to change over time as technology, marketing strategies for GE versus conventional crops, and consumer perceptions evolve.

References

Colorado State University, Department of Soil and Crop Sciences (2004). "Discontinued Transgenic Products," *Transgenic Crops: An Introduction and Resource Guide.*

Comis, D. (1997). *Safe corn pest bait expected to slash U.S. insecticide use.* U.S. Department of Agriculture, Agricultural Research Service.

Fernandez-Cornejo, J. (2004a). *The Seed Industry in U.S. Agriculture: An Exploration of Data and Information on Crop Seed Markets, Regulation, Industry Structure, and Research and Development.* AIB-786. U.S. Dept. Agr., Econ. Res. Serv., Feb.

Fernandez-Cornejo, J. (2004b). "Adoption of Genetically Engineered Crops in the U.S." Data product. U.S. Dept. Agr., Econ. Res. Serv.

Fernandez-Cornejo, J., and W.D. McBride (2002). *The Adoption of Bioengineered Crops*. AER-810. U.S. Dept. Agr., Econ. Res. Serv., May.

Fernandez-Cornejo, J., M. Caswell, and C. Klotz-Ingram (1999). "Seeds of Change: From Hybrids to Genetically Modified Foods," *Choices* (Millennium issue, 4th quarter): pp. 18-22.

International Service for the Acquisition of Agri-biotech Applications (ISAAA) (2004). *Preview: Global Status of Commercialized Biotech/GM Crops:* ISAAA Briefs 32-2004.

NRC (National Research Council) (2002). *Animal Biotechnology: Science Based Concerns.* Board on Agriculture and Natural Resources, Board on Life Sciences, The National Academies Press. Washington, DC.

Panos (1998)."Greed or Need? Genetically Modified Crops." Panos Media Briefing No. 30, Oct.

Pew Initiative on Food and Biotechnology (2001). *Harvest on the Horizon: Future Uses of Agricultural Biotechnology.* Available at http://pewag-biotech.org/research/harvest/

Price, G.K., W. Lin, and J. Fernandez-Cornejo (2003). *The Size and Distribution of Market Benefits from Adopting Agricultural Biotechnology.* TB-1906. U.S. Dept. Agr., Econ. Res. Serv., Nov.

Shoemaker, R., J. Harwood, K. Day-Rubenstein, T. Dunahay, P. Heisey, L. Hoffman, C. Klotz-Ingram, W. Lin, L. Mitchell, W. McBride, and J. Fernandez-Cornejo (2001). *Economic Issues in Agricultural Biotechnology.* AIB-762, U.S. Dept. Agr., Econ. Res. Serv., Feb.

UC Vegetable Research and Information Center, Pest-Resistance Management (2005). "Insecticidal Bt-Potatoes." University of California.

U.S. Department of Agriculture (2004). "Agricultural Biotechnology, Frequently Asked Questions: What Is Biotechnology?"

Virginia Polytechnic Institute and State University (VT) (2005). "Information Systems for Biotechnology: Field Test Releases in the U.S."