## EPTD DISCUSSION PAPER NO. 87

# THE PAYOFFS TO AGRICULTURAL BIOTECHNOLOGY: AN ASSESSMENT OF THE EVIDENCE

**Michele C. Marra, Philip G. Pardey, and Julian M. Alston**

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# ABSTRACT

Transgenic crops are relatively new technologies being adopted rapidly in the United States and in a few other countries. The economic impacts of these technologies have, thus far, been estimated in a piecemeal fashion. The purpose of this study was to collect and characterize the economic evidence available to date, organize it, and determine if any general implications can be drawn from it. The general classes of economic impacts at the farm level are discussed. The types of studies that generate estimates of these benefits are also characterized and categorized in terms of the implications for measuring economic impacts when the set of things held constant in the type of study does not correspond to those that economic theory suggests. The evidence is presented, along with some general implications drawn from the analysis. These implications are: (1) growing transgenic cotton is likely to result in reduced pesticide use in most years and is likely to be profitable in most years in most U.S. states in the Cotton Belt, (2) Bt corn will provide a small but significant yield increase in most years across the U.S. Corn Belt, and in some years and some places the increase will be substantial, and (3) although there is some evidence of a small yield loss in the Roundup Ready® soybean varieties, in most years and locations savings in pesticide costs and, possibly, tillage costs will more than offset the lost revenue from the yield discrepancy. There is not yet enough evidence to generalize even these few conclusions to other countries. More farm-level studies in more years and across more locations are required before any additional implications can be drawn. Studies that measure the non-pecuniary benefits and costs of these technologies should be undertaken, as well.

KEYWORDS: agriculture, transgenic biotechnologies, economic rates of return

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## TABLE OF CONTENTS

1. Introduction ........ 1

2. The Current Status of Event Introduction and Farmer Adoption ........ 2

3. Types of Economic Impacts on Farms ........ 11

4. Sources of Bias In the Evidence ........ 17

5. Empirical Evidence of Farm-Level Impacts ........ 25

6. Aggregate Impacts ........ 30

7. Conclusion ........ 33

References ........ 37

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Michele C. Marra,[1] Philip G. Pardey,[2] and Julian M. Alston[3]

## 1. INTRODUCTION

The first transgenic crop was approved for commercial release less than 10 years ago. The Flavr-Savr® tomato, genetically engineered to delay softening so the tomato could ripen on the vine and retain its "fresh picked" flavor, was introduced commercially in the United States in 1994. It was a scientific success, but a colossal business failure. Although the tomatoes achieved the delayed-softening and taste-retention objectives of their developers, yields were poor, mechanical handling equipment turned most of them into mush before they got to market, and consumers weren't willing to pay enough of a premium over conventional fresh tomatoes to cover costs. The seeds of the biotechnology protests started with the Flavr-Savr®, too, when Jeremy Rifkin managed to persuade the Campbell's Soup Company not to use biotech tomatoes in its products (Kasler and Lau 2000).

Nevertheless, seven years later farmers in several countries where the transgenic crops have been approved for planting are devoting significant portions of acreage to them. Their costs and benefits at the farm level have been documented in ex ante economic studies, farmer testimonials in the farm press, and reports issued by national departments

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of agriculture. In addition, few studies have attempted to measure the impacts among producers and consumers and other participants in the marketing chain by aggregating up from the farm-level studies. Nevertheless, specific information is still sketchy for many of the events,[4] and the reported economic impacts vary widely in both size and magnitude, even within the same location and for the same event in some cases.

Most of the studies so far have been conducted in the United States, and the impacts have been measured under U.S. conditions. This is a natural consequence of the fact that transgenic crops were first developed in the United States, and subsequently first approved for adoption and adopted in the United States. With increasing adoption in other countries, especially in less-developed countries, in future there will be more potential to present a more-balanced global picture. This study critically examines evidence of economic impacts reported to date, to categorize the types of evidence by potential biases and provide a range of values for some of the impacts based on the available results from public research.

## 2. THE CURRENT STATUS OF EVENT INTRODUCTION AND FARMER ADOPTION

### EVENT INTRODUCTION

By early 2001, more than 187 crop events involving nine basic phenotypic (physical) characteristics have been deregulated or approved for planting, feed, or food use in at least one of 13 individual countries plus the countries of the European Union (E.U.).

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[4] An event is a specific gene insertion in a particular crop that results in a desired expressed trait in the crop. For example, insertion of the *Bt* cry1A(c) protein into various cotton varieties is considered to be one event.

Successfully modified traits important for the major agricultural crops include delayed ripening, herbicide tolerance, insect resistance, modified color or oil, controllable male fertility, and virus resistance (AGBIOS Inc. 2001). Table 1 lists the major agricultural crops by modified trait, country approving at least one event within the trait, and type of approval as of February 2001. The majority of the approved events have been for food uses and over a fifth involved approvals for food or livestock feed uses without planting approval, implying that livestock and feed producers in the relevant country must import the feed. Most of the approvals have been issued in Canada and the United States, with very few issued so far in developing countries.

**Table 1¾ Major transgenic crops by trait, country, and approval type**

| | | | Approval type | | |
|---|---|---|---|---|---|
| Crop | Trait | Country | Unconfined planting | Feed use | Food use |
| Canola | Herbicide-tolerant | Australia | | | ✓ |
| | | Canada | ✓ | ✓ | ✓ |
| | | European Union | | | |
| | | Japan | ✓ | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| | Herbicide-tolerant and controllable male fertility | Canada | ✓ | ✓ | ✓ |
| | | European Union | | | |
| | | Japan | ✓ | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| | Oil content | Canada | ✓ | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| Carnations | Delayed ripening | Australia | ✓ | | |
| | | European Union | ✓ | | |
| | Flower color | Australia | ✓ | | |
| | | European Union | | | |
| Chicory | Herbicide-tolerant and controllable male fertility | European Union | ✓ | | |
| Corn | Herbicide-tolerant | Argentina | ✓ | ✓ | ✓ |
| | | Australia | | | ✓ |
| | | Canada | ✓ | ✓ | ✓ |
| | | European Union | | ✓ | ✓ |
| | | Japan | ✓ | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |

| | | | | | |
|---|---|---|---|---|---|
| | Herbicide-tolerant and controllable male fertility | Canada | ✓ | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| | Insect-resistant | Argentina | ✓ | ✓ | ✓ |
| | | Australia | | | ✓ |
| | | Canada | ✓ | ✓ | ✓ |
| | | European Union | ✓ | ✓ | ✓ |

**Table 1¾ Major transgenic crops by trait, country, and approval type *(continued)***

| | | | Approval type | | |
|---|---|---|---|---|---|
| Crop | Trait | Country | Unconfined planting | Feed use | Food use |
| | | Japan | ✓ | ✓ | ✓ |
| | | South Africa | ✓ | ✓ | ✓ |
| | | Switzerland | | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| | Insect-resistant and herbicide-tolerant | Argentina | ✓ | ✓ | ✓ |
| | | Canada | ✓ | ✓ | ✓ |
| | | Denmark | | | ✓ |
| | | European Union | ✓ | ✓ | ✓ |
| | | Japan | ✓ | ✓ | ✓ |
| | | The Netherlands | | ✓ | ✓ |
| | | Switzerland | | ✓ | ✓ |
| | | United Kingdom | | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| Cotton | Herbicide-tolerant | Argentina | ✓ | | |
| | | Australia | ✓ | | ✓ |
| | | Canada | ✓ | ✓ | ✓ |
| | | Japan | ✓ | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| | Herbicide-tolerant and insect-resistant | Japan | ✓ | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| | Insect-resistant | Argentina | ✓ | ✓ | ✓ |
| | | Australia | ✓ | ✓ | ✓ |
| | | Canada | | ✓ | ✓ |
| | | China | ✓ | ✓ | ✓ |
| | | Japan | ✓ | ✓ | ✓ |
| | | Mexico | ✓ | ✓ | ✓ |
| | | South Africa | ✓ | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| Melon | Delayed ripening | United States | ✓ | | ✓ |
| Papaya | Viral-resistant | United States | ✓ | | ✓ |
| Potato | Insect-resistant | Canada | ✓ | ✓ | ✓ |
| | | Japan | | | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| | Insect-resistant | Canada | ✓ | ✓ | ✓ |

| | | | | | |
|---|---|---|---|---|---|
| | and viral-resistant | United States | ✓ | ✓ | ✓ |
| Rice | Herbicide-tolerant | United States | ✓ | ✓ | ✓ |
| Soybeans | Herbicide-tolerant | Argentina | ✓ | ✓ | ✓ |
| | | Australia | | | ✓ |
| | | Brazil | ✓ | ✓ | ✓ |
| | | Canada | ✓ | ✓ | ✓ |

**Table 1¾ Major transgenic crops by trait, country, and approval type *(continued)***

| | | | Approval type | | |
|---|---|---|---|---|---|
| Crop | Trait | Country | Unconfined planting | Feed use | Food use |
| | | European Union | | | |
| | | Japan | ✓ | ✓ | ✓ |
| | | Korea | | | ✓ |
| | | Mexico | ✓ | ✓ | ✓ |
| | | The Netherlands | | ✓ | ✓ |
| | | Russia | | | ✓ |
| | | Switzerland | | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| Soybeans *(continued)* | | Uruguay | ✓ | ✓ | ✓ |
| | Oil content | Australia | | | ✓ |
| | | Canada | ✓ | ✓ | ✓ |
| | | Japan | ✓ | ✓ | |
| | | United States | ✓ | ✓ | ✓ |
| Squash | Viral-resistant | Canada | | | ✓ |
| | | United States | ✓ | | ✓ |
| Sugar Beets | Herbicide-tolerant | Canada | | | ✓ |
| | | Japan | | ✓ | ✓ |
| | | United States | ✓ | ✓ | ✓ |
| Tobacco | Herbicide-tolerant | European Union | | | |
| Tomatoes | Delayed ripening | Canada | | | ✓ |
| | | Japan | ✓ | | ✓ |
| | | Mexico | ✓ | ✓ | ✓ |
| | | United States | ✓ | | ✓ |
| Wheat | Herbicide-tolerant | Canada | ✓ | ✓ | ✓ |
| *Total* | | | *66* | *64* | *81* |

Source: Adapted from AGBIOS Inc. (2001), using data from "Crops and Traits," "Genetic Elements," and "Regulatory Approvals."

Note: United States data presented here as “Food use” and "Feed use” correspond with the AGBIOS “Food/Feed” entries, with the exception of tomatoes, papayas, and squash, which are listed here only under “Food use” because the Food and Drug Administration (2001) has approved these technologies and crops as “Human Food" only.

Approval processes and intellectual property rights (IPR) laws vary across jurisdictions and, in many instances, are still being developed for these unique products, so it is not surprising that only a handful of countries have issued approvals to date. The lists of modified traits and events for which applications are pending in at least one country are lengthening, however (AGBIOS 2001).

## ADOPTION

In those countries where planting approval has been granted and seed is available in sufficient quantities, farmers are generally adopting the new technologies fairly rapidly (Table 2). So far, U.S. farmers have been the keenest adopters of transgenic crops, both in terms of absolute acreage planted and the share of the total harvested area of those crops for which at least one transgenic planting approval exists. The proportion of transgenic acreage in Canada and the United States declined notably from 1999 to 2000, though it appears to have recovered in 2001, principally because of a substantial increase in the share of U.S. soybean acreage planted to transgenic varieties and continuing growth in the cotton acreage sown to transgenics (NASS 2001).

**Table 2¾ Transgenic acreage**

| Country | Year | Total transgenic acres | Total harvested area of crops with at least one approved event | Share |
|---|---|---|---|---|
| | | *(million acres)* | | *(percentage)* |
| Argentina | 1996 | 0.3 | 23.4 | 1.3 |
| | 1997 | 3.5 | 26.4 | 13.1 |
| | 1998 | 10.6 | 27.2 | 39.0 |
| | 1999 | 16.6 | 28.2 | 58.7 |
| | 2000 | 24.7 | 29.4 | 84.1 |
| Australia | 1996 | <0.2 | 0.8 | — |
| | 1997 | 0.2 | 0.9 | 26.5 |
| | 1998 | 0.2 | 0.9 | 26.2 |
| | 1999 | 0.2 | 1.1 | 22.4 |
| | 2000 | 0.5 | 1.2 | 41.1 |
| Canada | 1996 | 0.2 | 41.3 | 0.6 |
| | 1997 | 3.2 | 43.2 | 7.4 |
| | 1998 | 6.9 | 42.6 | 16.2 |
| | 1999 | 9.9 | 42.2 | 23.4 |
| | 2000 | 7.4 | 42.0 | 17.6 |
| China | 1998 | 0.5 | 11.0 | 4.5 |
| | 1999 | 0.7 | 9.2 | 8.1 |
| | 2000 | 1.2 | 10.0 | 12.4 |
| United States | 1996 | 10.7 | 158.1 | 6.7 |
| | 1997 | 25.2 | 165.1 | 15.2 |
| | 1998 | 60.4 | 166.4 | 36.3 |
| | 1999 | 78.5 | 166.1 | 47.3 |
| | 2000 | 69.6 | 169.6 | 41.0 |
| | 2001 | 82.3 | 167.8 | 49.0 |

Sources: For Australia, Argentina, Canada, and China, "Total transgenic acres" are from James (1997, 1998, 1999, and 2000b) and "Total area of crops" is from FAO (2000). For United States the share of acreage sown to transgenic crops for 1996–99 is from ERS (2001), and for 2000 and 2001 from NASS (2001). Corresponding total crop acreages were obtained from NASS (2001).

Note: Data represent transgenic acreages of crops with at least one approved event. For Australia and China, the data represent area under cotton; for Argentina, the area under soybeans, maize, and cotton; for Canada, the area under canola, maize, potatoes, soybeans, and wheat; and for the United States, the area planted to cotton, maize, and soybeans.

Table 3 lists the percentage of crop acreage planted to transgenic crops by U.S. state in 2001. Herbicide-tolerant soybeans—mostly Roundup Ready® (RR)—are now planted on about two-thirds of the soybean acreage throughout the United States. About one-quarter of the corn acreage in the United States was planted to transgenic varieties in 2001, of which most were insect resistant with a small percentage (6 percent) being herbicide-tolerant or combining herbicide tolerance with insect resistance. Transgenic cotton was adopted on a majority of cotton acreage in most southeastern U.S. states in 2001 and over one-quarter of California's cotton acreage. An important reason for different adoption rates across geographic regions has been the lag in getting the genetic trait into varieties appropriate for the different regions. This is especially true for cotton in Texas. The cotton variety laws in California have hindered adoption in that state, but some transgenic varieties are now becoming available there.

**Table 3¾ Transgenic crops by state and U.S. total, percentage of planted crop acres, 2001**

| | | Transgene type | | | |
|---|---|---|---|---|---|
| Crop | State | Herbicide-resistant | Insect-resistant | Stacked gene | All transgenic varieties |
| | | | *(percent)* | | |
| Corn | Illinois | 3 | 12 | 1 | 16 |
| | Indiana | 6 | 6 | | 12 |
| | Iowa | 6 | 25 | 1 | 32 |
| | Kansas | 11 | 26 | 1 | 38 |
| | Michigan | 7 | 8 | 2 | 17 |
| | Minnesota | 7 | 25 | 4 | 36 |
| | Missouri | 8 | 23 | 1 | 32 |
| | Nebraska | 8 | 24 | 2 | 34 |
| | Ohio | 4 | 7 | | 11 |
| | South Dakota | 14 | 30 | 3 | 47 |
| | Wisconsin | 6 | 11 | 1 | 18 |
| | Other Corn States | 8 | 11 | 1 | 20 |
| | *United States* | *7* | *18* | *1* | *26* |
| Cotton | Arizona | 29 | 21 | 28 | 78 |
| | California | 27 | 11 | 2 | 40 |
| | Georgia | 43 | 13 | 29 | 85 |
| | Louisiana | 14 | 30 | 47 | 91 |
| | Mississippi | 15 | 10 | 61 | 86 |
| | North Carolina | 37 | 9 | 38 | 84 |
| | Texas | 35 | 8 | 6 | 49 |

**Table 3¾ Transgenic crops by state and U.S. total, percentage of planted crop acres, 2001 *(continued)***

| | | Transgene type | | | |
|---|---|---|---|---|---|
| Crop | State | Herbicide-resistant | Insect-resistant | Stacked gene | All transgenic varieties |
| | Other Cotton States | 33 | 18 | 33 | 84 |
| | *United States* | *32* | *13* | *24* | *69* |
| Soybeans | Arizona | 60 | | | 60 |
| | Illinois | 64 | | | 64 |
| | Indiana | 78 | | | 78 |
| | Iowa | 73 | | | 73 |
| | Kansas | 80 | | | 80 |
| | Michigan | 59 | | | 59 |
| | Minnesota | 63 | | | 63 |
| | Mississippi | 63 | | | 63 |
| | Missouri | 69 | | | 69 |
| | Nebraska | 76 | | | 76 |
| | North Dakota | 49 | | | 49 |
| | Ohio | 64 | | | 64 |
| | South Dakota | 80 | | | 80 |
| | Wisconsin | 63 | | | 63 |
| | Other Soybean States | 64 | | | 64 |
| | *United States* | *68* | | | *68* |

Source: NASS (2001).

The astounding early adoption rates provide indirect evidence of potentially large, positive farm-level returns for many of these crops, at least for a significant number of farmers. For many purposes, more explicit evidence is needed on the farm-level gross and net benefits from these technologies. As is discussed below, farm-level impacts are difficult to estimate, and typical approaches are susceptible to bias.

Other measures of benefits, going beyond the farm level, are of interest for some purposes, and estimates of these benefits often depend on measures of impacts at the farm level; an additional reason for wanting to obtain unbiased and precise estimates. For instance, when estimating aggregative welfare measures, a small mistake in estimating the underlying farm-level impacts can result in over- or underestimating the shift in product supply, which in turn can result in a distorted measure of the change in industrywide profit or economic welfare. One cannot accurately predict future demand for a particular transgenic variety using incorrect estimates of impacts at the farm level. Because many transgenic varieties have environmental as well as pecuniary implications, an error in predicting future demand at the farm level can result in mismeasurement (and mismanagement) of the environmental impact.

Clearly, it is important to get the farm-level impacts right, and a critical examination of the economic impact evidence to date is a useful exercise at this early stage of the innovation process.

## 3. TYPES OF ECONOMIC IMPACTS ON FARMS

### YIELD

Many transgenic technologies in crops are designed to reduce yield losses from pests. These are generally the ones that insert genes that code for pesticides, such as the *Bacillus thuringiensis [Bt]* crops (corn, cotton, and potatoes). These crops can be thought of as pesticide-inherent crops. The pesticide kills pests that eat the plant, thus providing an effective and virtually complete pest control mechanism, at least in the short run. If these particular pests are present but are not in sufficient numbers to significantly affect yield, or if the pests affect yield but are cheap to control by other means, then the producer of pesticide-inherent crops may not experience a net benefit. If the pests are prevalent to an economically damaging extent in the area, however, then this complete control can result in significant yield increases. The pesticide-inherent crops may reduce yield risk, as well. Most farmers are averse to yield variability (as evidenced by crop-insurance purchases and by researcher measures of farmers' past attitudes toward risk). Those farmers would be willing to pay a little extra for seed in exchange for reduced yield variability.

## PEST-CONTROL COSTS

*Direct cost reduction.* Many studies show that pesticide-inherent crops reduce the number of sprays required to control pests. If reduced pest-control costs outweigh the additional cost of the seed, then farmers gain. Herbicide-tolerant crops also can significantly reduce savings in weed-control costs. RR cotton is a good example. Before the introduction of this herbicide-tolerant crop, there were no cotton herbicides that could be sprayed over the top of the cotton crop to control weeds (Carpenter and Gianessi 2001). Now, post emergence, over-the-top sprays are substituted for more expensive preplant incorporated applications of herbicides and mechanical cultivation to control weeds. Also, fewer weed-control field operations may be needed, which can result in significant savings.

*Indirect effects.* Three indirect economic effects can result from the adoption of transgenic crops. First, as farmers widely adopt these crops the demand for conventional counterparts and competing pesticides and herbicides may decrease, which may, in turn, reduce prices for the transgenic systems (Gianessi and Carpenter 2000). All farmers, including nonadopters of the transgenic varieties, will benefit from reduced pesticide and herbicide prices. Second, field operations are saved with many of the transgenic crops; releasing resources for other crops at crucial times during the growing season, allowing farmers to better manage those crops. For instance, the timing of soybean planting can have a major effect on weed control. If planting is delayed, weeds can begin to compete before the soybean canopy closes, causing lower soybean yields, higher weed-control costs, or both. Growers that plant herbicide-tolerant cotton on part of the farm have more time to plant their soybeans in a timely manner during the planting period.

Farmers may also benefit from increased flexibility. Many chemical alternatives to the herbicide-tolerant crops (for example, conventional cotton treated with a weed-control system that includes the relatively new herbicide, Staple®) present carry-over problems so that farmers cannot plant certain crops in the next growing season. Herbicide-tolerant crops, used in conjunction with short-lived herbicides, eliminate this constraint in many cases. Farmers may also be able to strip-crop or practice conservation tillage more easily with transgenic crops (Fernandez-Cornejo et al. 1999).

## PEST SUSCEPTIBILITY TO SUBSTITUTE PESTICIDES

*Conventional farming operations.* For a particular pesticide, whether inherent in the plant or not, pest resistance can develop with use over time, reducing pest control and, therefore, the comparative yield gains or cost savings. This has been a concern of scientists and policymakers and has resulted in rules to help slow the development of resistance. Bt cotton farmers in the United States are required to plant either 20 percent of their cotton land to a conventional variety using conventional pest control or approximately 4 percent to a conventional variety with no pest control.[5] Also, in order to preserve pest susceptibility to *Bt* in cotton, restrictions limit how much *Bt* corn can be planted in a county with significant cotton acreage. Because the transgenic crop is more profitable, or presumably would not have been planted, these requirements reduce farmers' net benefits

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[5] For the 2001 season, some "embedded refuge" (where the refuge is embedded as a contiguous block within a Bollgard cotton field) or "community refuge" options were also allowed. With pesticide -inherent crops, some pests with resistance may survive. Providing a portion of the field where susceptible pests can survive and mate with the resistant pests is intended to slow the rate of resistance buildup.

in the short run. Cross-commodity refuge requirements of this type are imposed by the U.S. Environmental Protection Agency (triggered by a minimum acreage of cotton at the county level). Compliance with these and other refuge requirements is monitored by seed companies, but the monitoring is expensive and compliance is incomplete, in some regions more than others (EPA 2000).

On the other hand, a major group of conventional insecticides for southeastern U.S. cotton, the pyrethroids, has been developing serious resistance problems in the bollworm/budworm complex of insects in some areas of the Deep South, and adoption of the *Bt* varieties is slowing development of the insects' resistance to these and other conventional pesticides. This preserves pesticide choices for farmers for a longer period, a farm-level and regional benefit from adoption of the transgenic varieties (Marra, Hubbell, and Carlson 1997).

*Organic farming operations.* *Bt* is an approved foliar insecticide for organic farming operations in the United States. Assuming refuge requirements do not completely halt resistance development to a particular *Bt* protein, adoption of transgenic *Bt* crops in a particular area increases the chances that foliar *Bt* will become a less effective insecticide for organic producers. Because organic producers have fewer pesticide options, the development of resistance will be costly for them in terms of lower yields and, perhaps, lower prices from decreases in quality.

## ENVIRONMENTAL EFFECTS

The use of chemical pesticides by farmers can involve risks to human health and to wildlife. Some of these effects—such as occupational health and safety risks for farmers and their families, as well as farm workers—can be thought of as “on-site” effects, confined to the farm and in relation to which farmers might be expected to have appropriate incentives. Farmers also might take into consideration some impacts on plant and animal populations on the farm, but other members of society might also attach a value to some on-site impacts (e.g., effects on an endangered species), and this could mean that the farmer and national incentives do not coincide.

Other environmental effects of chemical pesticides are “off-site,” through pesticide drift or pollution of ground water, and it is less clear that farmers will have appropriate incentives in relation to these impacts on other humans or plant and wildlife populations. The value attached to off-site effects by the farmers using the technology in many cases will be small relative to the values for others who are affected, including farm and non-farm neighbors as well as environmentalists. Transgenic technologies have the potential to reduce some of the negative on-site and off-site environmental impacts of chemical pest-control technologies. At the same time, however, concerns have been raised about the potential “environmental” impacts of the transgenic technologies themselves.

*Farmer and worker health.* So far, the pesticide-inherent varieties have contained biological insecticides, which are safer for humans and wildlife than their conventional counterparts (Gianessi and Carpenter 1999). Also, the pesticide-inherent crops involve no spray drift problems, special handling requirements, or reentry intervals, which can increase farmer and worker welfare in two ways. First, health concerns are reduced. These crops eliminate the inconvenience of complying with spray drift rules, purchasing and donning special safety clothing, and waiting to reenter the field after conventional application. Second, restricting pesticide applications to days and times when drift will not occur is costly, and pest control may not be timely or as effective. With pesticide-inherent crops, control is continuous throughout the growing season.

Most of the herbicide-tolerant crops are tolerant of glyphosate, one of the safest in the arsenal of currently available herbicides.

> Glyphosate has a half-life in the environment of 47 days, compared with 60–90 days for the herbicides it commonly replaces. The herbicides that glyphosate replaces are 3.4 to 16.8 times more toxic, according to a chronic risk indicator based on the EPA [Environmental Protection Agency] reference dose for humans (Economic Research Service 2000, 17).

Therefore, farmers and workers may experience fewer herbicide-related health effects when using this type of compound. Pesticide-inherent crops kill only pests that feed on the crop, and hence beneficial insects—those that feed on crop pests—are not harmed by this mode of pesticide delivery. This can enhance indirectly the effectiveness of the pesticide.

*Wildlife and water-quality effects.* As well as caring about their own and their workers' health and safety, farmers also care about the environment (Beach and Carlson 1993). Since transgenic crops are more environmentally benign than conventional crop/pesticide systems, farmer welfare should benefit from the favorable environmental impact of these crops compared with other crops that require conventional chemical pesticides. Glyphosate, for instance, binds to the soil and does not leach into groundwater or run off into surface water. Pesticide-inherent crops prevent any external effects associated with respraying, and the runoff and leaching of insecticides. In addition, other members of society who care about the environmental impacts will place a value on the on-site and off-site benefits from reducing the use of chemical pesticides.

*A caveat.* Concern about the gene insertion process itself still looms large, particularly in Europe at this writing, and this health concern could have a dampening effect on demand for transgenic crops, thus affecting the returns to farmers through lower prices, higher costs of identity preservation in the supply chain, or both. The recent recall by Frito-Lay, Inc. of consumer products potentially containing transgenic (Starlink®) corn is an example of the potential consequences of this concern. The proportion of U.S. corn acreage planted to transgenic varieties in 2000 fell by about a quarter from its 1999 level, but stabilized at this lower level in 2001.

## 4. SOURCES OF BIAS IN THE EVIDENCE

In this section we discuss various potential sources of bias in the evidence reported in the literature on impacts of transgenic technologies. Many of the issues raised here are not specific to the comparison of transgenic and conventional technologies; rather, they are general issues in evaluating technological alternatives, although the importance of particular issues may vary depending on the nature of the alternatives being compared.

### FIELD TRIALS

Through to December 2000, a reported 11,523 field trials of transgenic crops were conducted in 39 countries (Pardey and Beintema 2001). Most of the technology testing took place in developed countries: they accounted for about 84 percent of the trials, the United States alone, 55 percent. The traditional objective of field trials has been to quantify differences among the experimental treatments—very often different varieties (in variety trials) and, less often, different pest-control regimes or different cultural practices (fertilizer rates, tillage, irrigation, and so on). The effects measured almost always include yield and, in the case of trials of pest control or cultural practices, differences in input use. Sometimes economic comparisons (complete or not) accompany the physical evidence. Most of the transgenic crop field trials have been variety trials reporting yield only, although some also provide some information on differences in pesticide use.

Biases can be introduced into the resulting measures of farm-level impacts of the transgenic varieties in several ways (Table 4). Yield differences measured by variety trials typically hold everything else constant. The choice of varieties to be compared may also mean that the measured yield differences would be biased if used to represent the expected farm-level yield impacts. One class of variety trials compares the transgenic variety to its conventional parent, which generally is not among the set of conventional varieties farmers have chosen to grow in the area (because other varieties provide higher yields and/or greater net benefits). So, although this yield difference directly measures the change in yield provided by the transgene, it will overestimate the farm-level impact of adopting the transgenic variety.

**Table 4¾ Potential bias in measured economic impact by field trial type and transgene trait**

| | Transgene trait | |
|---|---|---|
| Type of field trial | Herbicide-tolerant | Pesticide-inherent |
| *Direction of potential bias in the measured economic impact* | | |
| Simple variety trials | | |
| Currently used conventional versus transgenic | downward | downward |
| Conventional transgenic parent versus transgenic | upward | upward |
| Pesticide use trials | uncertain | downward |
| On-farm, side-by-side comparisons | None if farmer-chosen inputs, otherwise downward | none |

Source: Developed by authors.

Economic impacts calculated from side-by-side variety trials of pesticide-inherent transgenic and conventional varieties (for example, *Bt* crops) can be biased by the halo effect. The insect suppression of the *Bt* crop may spill over onto the conventional treatment, providing another source of pest control, which may increase the yield relative to what it would be if the conventional crop were grown in isolation. The measured yield difference between the conventional and transgenic variety may be biased downward as a result.

Biases can be introduced into the measures of economic impact by the type of field trials that measure differences in pesticide use, as well. Agricultural scientists typically manage pests in field trials to maximize yield, not profit. Therefore, the pest-control regimes tested in the field trials may not reflect what a profit-maximizing farmer would use. The direction of this bias is difficult to predict if the transgenic crops tested are herbicide-tolerant. In the case of pesticide-inherent crops, the measured difference in pesticide use, thus the economic impact, may be underestimated.

Alston, Norton, and Pardey (1998) discuss the importance of defining the relevant counterfactual when evaluating the impact of a particular technology. The correct comparison, to ensure that farm-level impacts are measured accurately, is one where the set of practices and input mixes that would minimize costs (or maximize profits) is employed under each technology. The current conventional crop/pesticide system is the relevant counterfactual to compare with the new technology. This comparison is made most directly on farms where partial adoption has occurred. Although experiments set up on farms where farmers control the cultural practices for both technologies can be used to measure the impact, biases may still be introduced if some of the decisions are left to the researchers, and these decisions differ from those farmers would make.

A remaining source of potential bias arises when farmers alone make all the decisions. If farmers assign fields other than randomly between the technologies (that is, taking into account the recent cropping history, the natural fertility, or pest incidence, or other factors that determine the relative profitability of the alternatives), the comparison may be distorted. For instance, farmers might plant herbicide-tolerant varieties on heavily weed-infested fields to “clean them up,” and traditional varieties on cleaner fields. The advantage of the herbicide-tolerant variety in weed-infested conditions would be masked in a simple comparison that would implicitly assume the fields were identical. Furthermore, the dynamic benefits from the cleanup would be left out of a simple assessment. So, too, a downward bias in measuring economic impact could result if pesticide-inherent crops are grown in remote fields where pest control is generally more difficult, or if they are grown primarily in fields with heavier infestations of both target and nontarget pests.

## FARMER SURVEYS

Two general types of farmer surveying methods are used to gather evidence on the economic impact of transgenic crops: area-frame surveys by the U.S. Department of Agriculture (USDA), and whole-farm surveys by individual researchers or by marketing research firms. Each method has advantages and disadvantages.

*Field-level surveys.* The USDA and other national departments of agriculture acquire data about production practices, costs, and returns periodically using a combination of area-frame and list-frame sampling techniques. The area-frame sampling technique uses various types of geographic representations of land area to divide it into small segments (about one square mile). Then a random sample of these segments is chosen for further study. Usually, field investigators personally interview the operator of the land in a chosen segment (NASS no date). During the personal interview, a further randomization takes place to choose one field about which to ask detailed questions about production practices, costs, returns, or other desired information. For example, on the 1999 Agricultural Resource Management Study (ARMS) Upland Cotton Production Practices Report, the only farm-level questions about production practices, costs, or returns are "How many acres of cotton did this operation plant this year?" and "What is the total number of upland cotton fields that were planted this year?" (NASS 1999, 2). The rest of the production questions pertain to the randomly selected field.

One survey question asks the type of seed used in the field (genetically modified, herbicide-resistant *Bt* variety for insect resistance, variety with both insect and herbicide resistance, or other). If the farmer reported "other," there is no way to tell whether the field is part of a farm where transgenic technology has not been adopted at all or if it just happens to be a field on a farm where there is partial adoption (either true partial adoption or a required refuge field where conventional cotton is grown). Since there have been demonstrated differences between adopters and nonadopters of almost all new agricultural technologies or techniques that can also influence yield, production practices, production costs, or returns, the economic impact due solely to the technology cannot be known from this type of survey. For example, the difference in yield between the transgenic crop and the conventional crop cannot be calculated on each farm under the same management and general growing conditions. It can only be calculated as an average of all selected fields planted with the transgenic crop against the average of all fields not planted with the transgenic crop.

USDA National Agricultural Statistics Service (NASS) surveys have a large sample size, are conducted in person (producing a high response rate), and are generally conducted over a number of years with largely the same questions asked each time, so they are the only source of long-term, national, public information about these technologies. Several marketing firms have conducted surveys for the companies producing the technologies, but this information is not available in the public domain.

*Farm-level surveys*. The only way to hold constant the other factors that can influence the difference between the two technologies is to ask adopting farmers about the transgenic acres and the nontransgenic acres on their farm. They are the optimizers, both in their choice of whether or not to adopt and in the input choices and production method for each technology. As noted above, this also means that optimizing farmers will choose to allocate their transgenic and nontransgenic acres according to the relative advantages of the alternatives within their farm, which means that each variety will do better on average than if the varieties had been assigned at random among acres. Hence, a comparison of commercial performance of varietal technologies, even within a farm, would tend to understate the impact of adoption of the new technology, which presumably has been applied where it does comparatively better.

Table 5 illustrates the role of optimizing behavior. These data are taken from a 1996 farm-level survey by North Carolina State University and the University of Georgia. A total of 1,000 cotton farmers from the four southeastern states (Alabama, Georgia, North Carolina, and South Carolina) were surveyed by mail, with a follow-up mailing and some telephone follow-up. The proportion of regional cotton acreage in each state was used to stratify the sample. The usable response rate was 36 percent (Marra, Hubbell, and Carlson 1997).

**Table 5¾ Comparing means of different groups of respondent farmers and farms: The case of *Bt* cotton impacts in the southeast, 1996**

| Indicator/state | Group comparison<br>Adopters who planted both: *Bt* versus conventional acres | Adopters' *Bt* acres versus nonadopters' conventional acres | All farms: All *Bt* acres versus all conventional acres |
|---|---|---|---|
| Yield difference | | *(pounds lint per acre)* | |
| Alabama | 166 | 230 | 206 |
| Georgia | 84 | 216 | 158 |
| North Carolina | –3.2 | –11 | –14 |
| South Carolina | 119 | 113 | 109 |
| Insecticide cost difference | | *(dollars per acre)* | |
| Alabama | 3.10 | –2.34 | –0.87 |
| Georgia | –29.67 | –34.81 | –28.07 |
| North Carolina | –27.49 | –16.95 | –17.68 |
| South Carolina | –31.12 | –20.51 | –23.93 |
| Spray number difference | | *(number of insecticide applications per acre)* | |
| Alabama | 0.31 | –0.06 | 1.81 |
| Georgia | –2.68 | –1.26 | 1.70 |
| North Carolina | –2.38 | –2.11 | 2.51 |
| South Carolina | –2.46 | –2.47 | 0.46 |

Source: Marra, Hubbell, and Carlson (1997).

Economic impacts of transgenic crops, in terms of differences in yield, insecticide cost and pesticide use differences, are calculated three ways in Table 5. The first column of numbers represents differences between the two technologies (*Bt* cotton and conventional cotton) calculated within an adopting farmer's farm. The last column represents differences calculated as if the data came from a field-level survey, similar to the NASS surveys described above. Notice the disparity between the two estimates in every category. There are two contributing factors. Farmers who do not adopt the technology are either: (a) less educated with smaller farms and generally lower yields (which would make the difference in yields larger in the "all farms" column and the pesticide use differences smaller), or (b) operating farms with higher yields and less pest pressure to begin with (which would make the difference in yields smaller in the "all farms" column and the pesticide use differences larger) (Marra, Hubbell, Carlson 2001 and Ervin et al. 2000). Therefore, although we cannot assign any particular bias to the numbers calculated from field-level surveys, we can say they are likely to be different compared with the impacts calculated from within-farm comparisons.

Comparing the difference in the number of insecticide applications per acre across the columns highlights this point. In the within-farm comparison, there is either a very slight increase or a significant decrease in insecticide sprays on the transgenic acres, while the "all farms" column shows a consistent increase in insecticide sprays. The estimates in the middle column also illustrate the degree to which grouping of observations or survey methods can change the estimates. Given that these types of comparisons are quoted in the popular press and used by other researchers and interest groups, errors of this magnitude can cause grave concern (Wolfenbarger and Phifer 2000). It is important to get these numbers right.

The calculations in Table 5 are examples of the great differences one can encounter when the underlying survey methodology differs. These comparisons should be made over a number of crop years before confidence can be placed in any systematic biases found in the estimates. Estimates over time from the same source are not available, but in some cases for some transgenic crops, we can begin to make the first, tentative estimates of some of the economic impacts at the farm level based on information from a combination of field trials that mimic farmer production practices; on-farm, side-by-side comparisons; and farmer or consultant surveys. This empirical evidence is the subject of the next section.

## 5. EMPIRICAL EVIDENCE OF FARM-LEVEL IMPACTS

A search of the relevant academic journals, Internet searches, and inquiries of researchers who work in this area produced a number of estimates of several measures of farm-level impacts associated with commercially available transgenic crops.[6] Some ex ante estimates were discovered, as well. Estimates of yield differences, revenue differences, pesticide cost differences, pesticide use differences, and net returns to transgenic crops were collected directly where available or, where possible, imputed from the reported information. Sources examined fall into one of the following categories: the various types of field trials listed in Table 4, farmer and consultant surveys, studies reporting ex ante estimates of economic impacts, or field-level surveys.[7]

The estimates from 6 studies (out of the total of 75 studies) were eliminated from consideration at the outset on the grounds that they would be misleading. Specifically, we excluded estimates if it was not possible to say whether they referred to (a) a within-farm comparison for an adopting farmer, which is what is desired, rather than (b) a comparison

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[6] Several studies, including York and Culpepper (1999) and Wilcut et al. (1999) report only percentage changes, which cannot be compared directly with measures from the studies presented here.

[7] All of the data collected are presented in Appendix Table 1. Though the estimates in the appendix are not an exhaustive list (particularly in light of the large number of unpublished field trials and market surveys that are not accessible in the public domain), they should be sufficient to begin to make some inferences about farm-level impacts.

between adopting and non-adopting farmers, which does not hold the right things constant. Then, for groups of studies in which enough estimates remained for a particular combination of impact measure, location, and transgene type, the mean and a range of the estimates are reported in Tables 6 and 7, by crop and event.

## Table 6¾ Summary of farm-level impact evidence for *Bt* cotton

| | Differences in: | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Yield | | | | Pesticide cost | | | | Pesticide use | | | | Profit | | | |
| State | Number of estimates | Mean | Minimum | Maximum | Number of estimates | Mean | Minimum | Maximum | Number of estimates | Mean | Minimum | Maximum | Number of estimates | Mean | Minimum | Maximum |
| BT COTTON | *(count)* | *(pounds lint per acre)* | | | *(count)* | *(dollars per acre)* | | | *(count)* | *(sprays per acre)* | | | *(count)* | *(dollars per acre)* | | |
| Alabama | 4 | 143.5 | 38.0 | 231.5 | 2 | –32.4 | 3.1 | –68.0 | 2 | –1.3 | 0.3 | –3.0 | 2 | 77.6 | 38.7 | 116.5 |
| Arizona | 8 | 116.7 | –331.5 | 917.0 | 9 | 17.1 | 97.0 | –24.6 | 3 | –2.2 | –1.8 | –2.5 | 10 | 57.5 | –104.0 | 465.0 |
| Georgia | 3 | 75.2 | 38.0 | 104.0 | 3 | –23.4 | 27.5 | –68.0 | 3 | –2.7 | –2.5 | –3.0 | 3 | 92.0 | 38.7 | 169.2 |
| Louisiana | 2 | –7.5 | –37.0 | 22.0 | 2 | –20.0 | –15.4 | –24.6 | 2 | –2.4 | –2.2 | –2.5 | 2 | 16.5 | –3.1 | 36.0 |
| Mississippi | 8 | 22.6 | –73.0 | 92.0 | 8 | –5.1 | 13.8 | –24.6 | 4 | –2.4 | –1.3 | –3.3 | 6 | 34.5 | –3.1 | 79.5 |
| North Carolina | 8 | 41.6 | –35.7 | 182.5 | 2 | –14.3 | –1.2 | –27.5 | 2 | –2.4 | –2.4 | –2.5 | 8 | 20.5 | –25.3 | 95.1 |
| Oklahoma | 4 | 168.0 | 123.0 | 203.0 | | | | | 4 | –3.4 | –2.3 | –6.5 | 4 | 53.8 | 25.5 | 85.5 |
| South Carolina | 2 | 90.5 | 62.0 | 119.0 | 2 | –16.2 | –1.2 | –31.1 | 2 | –2.5 | –2.5 | –2.5 | 4 | 51.8 | 17.1 | 80.1 |
| Tennessee | 2 | –79.0 | –243.0 | 85.0 | 1 | –5.6 | | | 1 | –1.8 | | | 2 | 67.5 | 60.7 | 74.3 |
| Texas | 3 | 116.6 | 81.0 | 177.5 | | | | | | | | | 1 | 46.0 | | |
| Virginia | 1 | 62.0 | | | 1 | –1.2 | | | 1 | –2.5 | | | 1 | 41.7 | | |
| China | 1 | 325.0 | | | 1 | –7.1 | | | | | | | 1 | 66.0 | | |
| Mexico | 1 | 182.0 | | | 1 | 36.0 | | | | | | | 1 | 173.0 | | |
| RR COTTON | | | | | | | | | | | | | 1 | 17.1 | | |
| Arkansas | 1 | –150 | | | | | | | | | | | | | | |
| Tennessee | 1 | –243 | | | 1 | –145.3 | | | | | | | 1 | 74.3 | | |
| BT/RR COTTON | | | | | | | | | | | | | | | | |
| Arkansas | 2 | 292.8 | –331.5 | 917.0 | 2 | 79.5 | –269.0 | 159.0 | | | | | 2 | 243.0 | 21.0 | 465.0 |

Source: Compiled by authors.

## Table 7¾ Summary of farm-level impact evidence for other technologies and crops

| | | Differences in: | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Yield | | | | Profit | | | |
| Transgene type | State | Number of estimates | Mean | Minimum | Maximum | Number of estimates | Mean | Minimum | Maximum |
| | | *(count)* | *(bushels per acre)* | | | *(count)* | *(dollars per acre)* | | |
| *Bt* corn | Corn Belt | 6 | 10.8 | 5.3 | 17.0 | 1 | 60.1 | | |
| | Illinois | 4 | 16.3 | 1.5 | 30.0 | 1 | 23.4 | | |
| | Iowa | 5 | 7.1 | 2.9 | 12.2 | | | | |
| | Kansas | 3 | 7.8 | 3.7 | 12.0 | | | | |
| | Minnesota | 1 | 18.2 | 18.2 | 18.2 | | | | |
| | Nebraska | 2 | 7.4 | 4.2 | 10.5 | | | | |
| | South Dakota | 2 | 10.3 | 7.7 | 12.9 | | | | |
| | United States | 5 | 6.7 | 3.3 | 12.0 | 3 | 4.8 | –1.8 | 18.0 |
| | | | *(bushels per acre)* | | | | | | |
| RR Canola | Australia | 2 | 24.49 | 7.62 | 41.36 | | | | |
| | Canada | 3 | –1.9 | –2.7 | –1.0 | 2 | 11.3 | –1.9 | 24.5 |
| | | | *(tons per acre)* | | | | | | |
| VR Potatoes | Mexico | 6 | 23.7 | 6.7 | 43.0 | 6 | 288.8 | 69.6 | 559.4 |
| | | | *(bushels per acre)* | | | | | | |
| RR Soybeans | Illinois | 5 | 1.3 | –0.3 | 1.8 | | | | |
| | Iowa | 3 | –3.4 | –4.0 | –2.8 | | | | |
| | Kansas | 1 | –3.0 | –3.0 | –3.0 | | | | |
| | Michigan | 3 | –2.2 | –2.5 | –1.7 | | | | |
| | Minnesota | 3 | –4.4 | –4.6 | –4.2 | | | | |
| | Nebraska | 3 | –4.4 | –5.8 | –2.1 | | | | |
| | North Carolina | 4 | 2.7 | –2.3 | 6.8 | 2 | 14.0 | 6.0 | 22.1 |
| | Ohio | 3 | –2.3 | –3.1 | –1.7 | | | | |
| | South Dakota | 3 | –3.8 | –5.0 | –2.4 | | | | |
| | Wisconsin | 3 | –1.2 | –2.0 | 0.1 | | | | |
| | | | *(tons per acre)* | | | | | | |
| IR Sweet Potatoe | Kenya | 2 | 12.1 | 7.8 | 16.3 | 2 | 65.5 | 42.3 | 88.6 |
| VR Sweet Potatoes | Kenya | 2 | 16.6 | 14.7 | 18.5 | 2 | 88.7 | 76.2 | 101.1 |
| *Bt* Irish Potatoes | Illinois | | | | | 3 | 15.5 | -4.6 | 37.2 |
| | United States | | | | | 3 | 22.4 | -1.8 | 51.0 |

Source: Compiled by authors.

Most of the impact measures to date have been for *Bt* cotton, *Bt* corn, and RR soybeans. The range of yield differences between *Bt* and conventional cotton appears quite large, mostly because of the wide range of pest incidence in the years since the commercial introduction of *Bt* cotton. Across the U.S. Cotton Belt, a much higher incidence of the bollworm/budworm complex that *Bt* cotton is designed to control occurred in 1997 than in 1996, for example. Even so, in 9 of the 11 states, average yields for *Bt* cotton exceeded those of conventional cotton. There is also evidence of reduced pesticide use with *Bt* cotton—on average, a reduction of between 1.3 and 3 pesticide sprays per season. Nine of 10 states report a reduction in average pesticide costs (Arkansas is the exception), while in all states where the data permit comparisons, *Bt* cotton was more profitable than its conventional counterpart. The mean profit advantage ranges from about $20 to almost $100 per acre, including the costs of the technology fee.

The most prevalent impact measure so far for *Bt* corn is the yield difference.[8] In most locations and years, however, the incidence of European corn borer is not thought to be significant enough to control with pesticides, so the yield difference is sufficient to calculate total additional monetary benefits. In the states where a range could be reported, all show an unambiguous yield increase with *Bt* corn, although one estimate (Illinois 1998) is below the break-even yield increase to cover the additional technology cost (assuming US$2.00 per bushel for the corn and an US$8.00 per acre technology fee). Studies estimating the impact of *Bt* corn across the Corn Belt give yield increases ranging from 5.3

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[8] An interesting and well-done study by Hyde et al. (2000) of the potential value of *Bt* corn in the Corn Belt gives ranges of values under various probabilities of European corn borer infestation (presumably corresponding to different sections of the Corn Belt) and risk attitudes, but they are not specific enough for the purposes of this discussion.

to 14.9 bushels per acre. The mean yield increases are all in the profitable range, with results for some states (Illinois and Minnesota) indicating substantial profitability from early adoption of *Bt* corn. If identity preservation does not become an issue, or if the costs of segregation are comparatively minor, then *Bt* corn should continue to be profitable.

Studies from Illinois and North Carolina show positive mean yield differences for RR soybeans, with yield gains of up to 6.83 bushels per acre in North Carolina in 1997. However, most of the available evidence for RR soybeans shows a slight drop in yields, the greatest of which is a loss of 5.7 bushels per acre in Nebraska in 1997. The only profit estimates available so far indicate a net return averaging $14 per acre to using RR soybeans in North Carolina. The results for RR soybeans are a good example of where the results from variety trials are insufficient to draw conclusions about the profitability of using transgenic versus conventional crop varieties. Although more research is required to be definitive, the widespread adoption of this technology clearly indicates that the production costs are sufficiently lower to make RR soybeans profitable for the vast majority of growing conditions and farm types throughout the United States.

## 6. AGGREGATE IMPACTS

A few studies have attempted to estimate the aggregate economic impact of a particular transgenic crop (or group of crops) and the distribution of the impact on the different sectors involved. Each of these has had to employ some measure of farm-level effects. Most of the studies present their results in terms of total welfare effects and the distribution of those effects under various scenarios, or assumptions, regarding parameters they view important.

Falck-Zepeda, Traxler, and Nelson (1999) model the change in welfare effects from adoption of *Bt* cotton and RR soybeans using a basic two-region framework (United States and ROW), based on the approach in Alston, Norton, and Pardey (1998), in which the farm-level benefit is allowed to vary among U.S. states creating several subregions. Falck-Zepeda, Traxler, and Nelson (FTN) use confidential market survey data, as well as published agronomic and farmer survey data to estimate their supply shifts in the United States and assume that the ROW either experiences the same or half of the efficiency gains as the United States. They find that, for the 1996 and 1997 crop, *Bt* cotton adoption generated large increases in global social surplus and significant increases in U.S. producer surplus at the expense of ROW producers. For RR soybeans in 1997, FTN find again, large global surplus increases and large U.S. producer surplus increases with relatively small decreases in producer surplus in ROW.

Moschini, Lapan, and Sobolevsky (1999) model the global welfare effects of RR soybeans. They develop a three-region world model that includes a monopolist technology seller as well as consumers and producers. They assume the technology results in a US$20 per hectare increase in profit at the farm level, based on conditions in Iowa in 1997–98. They estimate changes in consumer, producer, and total surplus for the United States, South America, and the rest of the world (ROW), and the surplus accruing to the monopolist. Moschini, Lapan, and Sobolevsky (MLS) generally find large increases in total social welfare from the technology, but mostly negative producer surplus changes in all regions. They examine the sensitivity of the results to the supply shift assumptions and find that halving or doubling of the profit change for any region can have a large impact on the size and distribution of the welfare changes.

Pray et al. (1999) consider the impact of *Bt* cotton in China. They collected farm-level data on the net benefits of the *Bt* varieties (Appendix Table 1) and, using the same basic modeling approach as MLS and FTN, estimate the distribution of benefits among farmers, seed companies, and research institutes/companies. They find significant aggregate net benefits to farmers and much smaller benefits to the seed companies and research institutes/companies. Pray et al. also present the only quantified farm-level nonpecuniary benefits we have found. They report that only 4 percent of farmers planting the *Bt* varieties suffered any effects of pesticide poisoning, compared with 33 percent of those who did not plant *Bt* cotton.

Some ex ante studies of the potential for transgenic crops in developing countries have been undertaken. One is a study of virus- and weevil-resistant sweet potatoes in Kenya (Qaim 1999) and another is a study of virus-resistant potatoes in Mexico (Qaim 1998). The farm-level benefits used in both studies are based on a consensus of expert opinion. The aggregate net benefits are calculated as changes in regional producer surplus and consumer surplus resulting from technical change. Qaim finds that central and eastern Kenyan producers would benefit much less than western producers and that the benefits accruing to all groups are greater for the weevil-resistance technology compared with the virus- resistance technology. In the Mexican case study, producers were divided into small, medium, and large farmers, and the benefits were measured with and without the potential for trade. Qaim reports that trade reduced the benefits to this small-country producer and that some trait and distribution assumption combinations favored small farms, while others favored the larger farms. In all cases, Qaim estimates a large net gain to all sectors and farm sizes.

All of the above studies of the aggregated effects of transgenic crop adoption were completed before the controversy over the safety of GM food grew to the point that identity preservation became an issue. Fulton and Keyowski (2000), in a theoretical modeling exercise, point to the importance of farmer heterogeneity in modeling the distribution of benefits when the transgenic and traditional markets are segregated.

Burton et al. (2000), using the same methodology as most of the other aggregate studies, considered the effects of various identity preservation schemes on the total and distributional aspects of the benefits from adoption of GM canola. Based on Fulton and Keyowski, they assume that adoption of GM canola decreased marginal costs at the farm level by 8.5 percent. They divide the world into consumers and producers of GM and non-GM canola and estimate the distribution of total surplus accruing to each group under various assumptions about the form of technical change, the incidence of identity preservation costs, and the impact of a technology fee. They find that, under most scenarios, consumers of the non-GM canola lose, while consumers of GM canola gain. Changes in producer surplus vary widely, depending on the assumptions listed above, but producers of the non-GM canola seem to fare better in most cases than the producers of the GM canola.

## 7. CONCLUSION

It is worth emphasizing again that estimates of farm-level impact summarized in Tables 6 and 7 are for a small number of locations and years. As more useful data become available for economic comparisons—both in the United States and more particularly in the rest of the world—, estimates of this type can be viewed with more confidence. It is fair to say only three things at this point with much confidence, and these apply only in the context of the United States (although they might be expected to have parallels in other countries).

- Growing transgenic cotton is likely to result in reduced pesticide use in most years in most states, and it is more likely than not to be a relatively profitable enterprise in most of the U.S. Cotton Belt.
- *Bt* corn will provide a small but significant yield increase in most years across the Corn Belt, and in some years and some places the increase will be substantial.
- Although there is some evidence of a small yield loss in the RR soybean varieties, in most years and locations savings in pesticide costs and, possibly, tillage costs will more than offset the lost revenue from the yield discrepancy.

There are still many farm-level impacts, the value of which no one has attempted to measure thus far. An important aspect is the "convenience factor" for the RR crops: farmers report that even if there is a slight "yield drag" with RR soybeans, the reduced herbicide costs and the extra time available to attend to their higher-value crops are more than sufficient compensation. The impressive rates of adoption for many of these transgenic crops are strong evidence of their perceived value to farmers. Only time will tell if consumer concerns will slow this pace significantly and permanently, but if these concerns can be addressed satisfactorily, then many of the first-generation transgenic crops are a win-win situation for farmers. They can expect higher profits and environmentally safer growing conditions. If identity preservation becomes a fact of life, then these farm-level benefits are much more open to question to the extent that either adopting farmers have to pay the costs of segregation or transgenic varieties incur significant price discounts.

Policymakers and consumers will benefit from better estimates of the farm-level benefits because they are part of the cost of regulation. Additional studies are warranted to estimate the potential pecuniary benefits more precisely by using on-farm results based on farmer decisions, especially in light of new developments at the final product level for some crops. It is time also for an initial attempt to quantify the nonpecuniary benefits.

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## Appendix Table 1--Ranges of benefits by crop, geographic area, and study

| Event | State/ Region/ Country[a] | Reference | Study type[b] | Period | Evidence (Transgenic – Conventional) per acre | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Yield | Herbicide cost | Number of herbicide sprays | Insecticide cost | Number of insecticide sprays | Profit |
| CORN | | | | | *(bushels)* | *(U.S. dollars)* | *(count)* | *(U.S. dollars)* | *(count)* | *(U.S. dollars)* |
| *Bt* | Iowa | Rice and Pilcher 1998 | A | 1997 | 7.6 | | | | | |
| | | Gianessi and Carpenter 1999 | A | 1997–98 | 2.9–12.2 | | | | | |
| | Illinois | Gianessi and Carpenter 1999 | A | 1997–98 | 1.5–17.4 | | | | | |
| | | European Commission 2000 | A | 1998 | 16.33 | | | | | 23.37 |
| | | The Economist 2000 | B | 1998 | 30 | | | | | |
| | Kansas | Gianessi and Carpenter 1999 | A | 1997–98 | 3.7–12 | | | | | |
| | | Sloderbeck, Buschman, Dumler, and Higgins 1999 | A | 1997–98 average | 7.7 | | | | | |
| | Minnesota | Rice and Pilcher 1998 | A | 1997 | 18.2 | | | | | |
| | Nebraska | Gianessi and Carpenter 1999 | A | 1997–98 | 4.2–10.5 | | | | | |
| | South Dakota | Gianessi and Carpenter 1999 | A | 1997–98 | 7.7–12.9 | | | | | |
| | U.S. Heartland | Hart 1999 | F[a] | 1997 | | | | | 0.06 | |
| | U.S. Corn Belt | European Commission 2000 | A | 1997 | 14.9 | | | | | |
| | United States | Gianessi and Carpenter 1999 | A | 1997–98 | 4.6–9.4 | | | | | |
| | U.S. Corn Belt | | A | 1997 | 10.8–17 | | | | | |
| | | | A | 1998 | 7 | | | | | |
| RR | U.S. Heartland | Hart 1999 | F[a] | 1997 | | | 0.3 | | | |
| COTTON | | | | | *(pounds lint)* | | | | | |
| *Bt* | Alabama | Jones et al. 1996 | A | 1994–95 | 138.5–231.5 | | | | | |
| | | Marra, Hubbell, and Carlson 1997 | B | 1996 | 165.9 | | | 3.1 | 0.31 | 116.48 |
| | | Mullins and Mills 1999 | A | 1998 | 38 | | | –67.99 | –3 | 38.74 |
| | Arkansas | Bryant, Robertson and Lorenz 1999 | A | 1996–97 | | | | 4.38–11.29 | | –26.95–86.74 |
| | | Bryant, Robertson, and Lorenz 1998 | A | 1997 | –24 | | | | | –25 |
| | | Mullins, and Mills 1999 | C | 1998 | 22 | | | –15.43 | –2.2 | 36.03 |

## Appendix Table 1¾ Ranges of benefits by crop, geographic area, and study *(continued)*

| | | | | | Evidence (Transgenic – Conventional) per acre | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Event | State/ Region/ Country[a] | Reference | Study type[b] | Period | Yield | Herbicide cost | Number of herbicide sprays | Insecticide cost | Number of insecticide sprays | Profit |
| COTTON *(continued)* | | | | | *(pounds lint)* | *(U.S.dollars)* | *(count)* | *(U.S.dollars)* | *(count)* | *(U.S.dollars)* |
| | | Benson and Hendrix 1999 | A | 1998 | –37 | | | –24.63 | –2.54 | –3.12 |
| *Bt*/RR | | Bryant, Allen, Bourland, and Earnest 1999 | A | 1998 | 917 | 62 | | 97 | | 465 |
| | | Bryant, Allen, Bourland and Earnest 1999 | A | 1998 | –331.5 | –366 | | 97 | | 21 |
| *Bt*/RR | | Bryant, Allen, Bourland, and Earnest 1999 | A | 1998 | 917 | 62 | | 97 | | 465 |
| *Bt* | | Bryant, Robertson, and Lorenz 1999 | A | 1998 | | | | –10.22 | | 64.52 |
| | | Capps, Allen, Earnest, Tugwell, Kharbouti 1999 | A | 1998 | 452 | | | | | |
| | | Mullins, and Mills 1999 | C | 1998 | 85 | | | –5.57 | –1.8 | 60.7 |
| | China | Pray, Ma, Huang, and Qiao 1999 | B | 1999 | 325 | | | –71 | | 66.3 |
| | Georgia | Marra, Hubbell, and Carlson 1997 | B | 1996 | 83.55 | | | –29.67 | –2.68 | 169.24 |
| | | Stark 1997 | C | 1996 | 104 | | | 27.5 | –2.5 | 68 |
| | | Mullins and Mills 1999 | A | 1998 | 38 | | | –67.99 | –3 | 38.74 |
| | Louisiana | Mullins and Mills 1999 | C | 1998 | 22 | | | –15.43 | –2.2 | 36.03 |
| | | Benson and Hendrix 1999 | C | 1998 | –37 | | | –24.63 | –2.54 | –3.12 |
| | Mexico | Magana et al. 1999 | A | 1998 | 182 | | | 36 | | 173 |
| | Mississippi | Wier, Mullins, and Mills 1998 | A | 1995 | 92 | | | –22.7 | | 79.5 |
| | | Cooke and Freeland 1998 | A | 1996 | –73 to 0 | | | 0–0.67 | | |
| | | Wier, Mullins, and Mills 1998 | A | 1996–97 | 46–84 | | | 1.87–5.19 | | 24.71–50.73 |
| | | Gibson et al. 1997 | A | 1996 | 47 | | | 13.84 | | 16.23 |
| | | Layton, Stewart, Williams, and Long 1998 | A | 1997–98 | | | | | –3.34 to –1.34 | |
| | | Mullins and Mills 1999 | C | 1998 | 22 | | | –15.43 | –2.2 | 36.03 |
| | | Benson and Hendrix 1999 | C | 1998 | –37 | | | –24.63 | –2.54 | –3.12 |
| | North Central | Jones et al. 1996 | A | 1994–95 | 63.5–182.5 | | | | | |

## Appendix Table 1--Ranges of benefits by crop, geographic area, and study *(continued)*

| | | | | | Evidence (Transgenic – Conventional) per acre | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Event | State/ Region/ Country[a] | Reference | Study type[b] | Period | Yield | ***Herbicide cost*** | Number of herbicide sprays | Insecticide cost | Number of insecticide sprays | Profit |
| COTTON *(contin ued)* | | | | | *(pounds lint)* | *(U.S. dollars)* | *(count)* | *(U.S. dollars)* | *(count)* | *(U.S. dollars)* |
| | North Central | Bacheler, Mott, and Morrison 1998 | D | 1996 | | | | | | 7.49–8.96 |
| | | Marra, Hubbell, and Carlson 1997 | B | 1996 | –3.21 | | | –27.48 | –2.38 | 3.54 |
| | | Mullins, and Mills 1999 | C | 1998 | 62 | | | –1.19 | –2.5 | 41.71 |
| | Oklahoma | Karner, Goodson, and Hutson 2000 | E | 1996–99 | 120–203 | | | | –6.5 to –2.3 | 25.46–85.53 |
| | South Carolina | Marra, Hubbell, and Carlson 1997 | B | 1996 | 119 | | | –31.12 | –2.47 | 80.06 |
| | | ReJesus, Greene, Hammig and Curtis 1997 | A | 1996 | | | | | | 68.44 |
| | | Mullins, and Mills 1999 | A | 1998 | 62–85 | | | –5.57 to –1.19 | –2.5 to –1.8 | 41.71–60.7 |
| | Texas | Jones et al. 1996 | A | 1994–95 | 91.4–177.5 | | | | | |
| | | Speed and Ferreira 1998 | A | 1996–97 | 80.6–81 | 2.11–9.09 | | | | 45.99–52.72 |
| | Virginia | Mullins and Mills 1999 | A | 1998 | 62 | | | –1.19 | –2.5 | 41.71 |
| | Cotton Belt | Hart 1999 | F[a] | 1997 | | | | –0.92 to –3.03 | | |
| RR | Mississippi Portal | Hart 1999 | F[a] | 1997 | | –1.32 | | | | |
| *Bt* | South Carolina | ReJesus Greene, Hammig, and Curtis 1997 | A | 1996 | | | | | | 17.12 |
| RR | Arkansas | Bryant, Allen, Bourlan, and Earnest 1999 | A | 1998 | –150 | 2 | | 0 | | –104 |
| | Tenessee | Slinsky, Edens, Larson, and Hayes 1998 | A | 1996 | –243 | –145.3 | | | | 74.26 |
| *Bt*/Rr | Arkansas | Bryant, Allen, Bourland and Earnest 1999 | A | 1998 | –331.5 | –366 | | 97 | | 21 |

## Appendix Table 1¾ Ranges of benefits by crop, geographic area, and study *(continued)*

| | | | | | Evidence (Transgenic – Conventional) per acre | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Event | State/ Region/ Country[a] | Reference | Study type[b] | Period | Yield | Herbicide cost | Number of herbicide sprays | Insecticide cost | Number of insecticide sprays | Profit |
| SOYBEANS | | | | | *(bushels)* | *(U.S.dollars)* | *(count)* | *(U.S.dollars)* | *(count)* | *(U.S.dollars)* |
| Ht | U.S. Heartland | Bryant, Allen, Bourland and Earnest 1999 | F | 1997 | | | –0.54 | | | |
| | Mississippi Portal | | F | 1997 | | | | | –0.53 | |
| | North Carolina | | F | 1997 | | | | | 0.07 | |
| Ht | Pacific Garden | Hart 1999 | F[a] | 1997 | | | | | –1.1 | |
| QE | United States | McVey, Pautsch, and Baumel 1995 | F | ex ante | | | | | | 0.49/bu–0.11/bu |
| RR | Illinois | European Commission 2000 | A | 1997 | 1.71 | | | | | |
| | Iowa | | A | 1997 | –3.42 | | | | | |
| | Kansas | | A | 1997 | –2.96 | | | | | |
| | Minnesota | | A | 1997 | –4.16 | | | | | |
| | Mississippi | Couvillion, Kari, Hudson, and Allen 2000 | F[a] | 1997–98 | | –6.69–4.24 | | | | –4.24–6.69 |
| | North Central | Harley 1999 | B | 1996–97 | 3.24–6.83 | | | | | |
| | | Dunphy and York 2000 | A | 1999 | –2.3 | | | | | |
| | | Coble 1997 | A | 1994–96 average | | | | | | 6 |
| | | Dunphy, Heiniger, and York 2000 | A | 1996–98 average | | | | | | 22 |
| | South Dakota | European Commission 2000 | A | 1997 | –4.16 | | | | | 22 |
| | Wisconsin | | A | 1997 | –1.59 | | | | | |
| | United States | Moschini, Lapan, and Sobolevsky 1999 | E | ex ante | 2.25 | | | | | 20 |
| | Michigan | European Commission 2000 | A | 1997 | –1.71 | | | | | |
| | Nebraska | | A | 1997 | –5.75 | | | | | |
| | Ohio | | A | 1997 | –1.71 | | | | | |

## Appendix Table 1¾ Ranges of benefits by crop, geographic area, and study *(continued)*

| | | | | | Evidence (Transgenic – Conventional) per acre | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Event | State/ Region/ Country | Reference | Study type | Period | Yield | Herbicide cost | Number of herbicide sprays | Insecticide cost | Number of insecticide sprays | Profit |
| CANOLA | | | | | *(bushels)* | *(U.S. dollars)* | *(count)* | *(U.S. dollars)* | *(count)* | *(U.S. dollars)* |
| RR | Australia | Pioneer Hybrid 2000 | A | 1999 | 7.82– 41.36 | | | | | |
| | Alberta, Canada | European Commission 2000 | A | 1998 | –2 to –1 | | | | | –84.97 to 95.51 |
| | Saskatchewan, Canada | | A | 1999 | –2.7 | –10 | | | | –16.83 |
| IRISH POTATOES | | | | | *(hundredweight)* | | | | | |
| *Bt* | United States | Gianessi and Carpenter 1999 | F | 1997–98 | | | | | | –1.81 to 18 |
| | Illinois | | F | 1996–98 | | | | | | –4.63 to 37.24 |
| | North West United States | | F | 1998 | | | | | | 51 |
| Virus-resistant PVX-PVY | Mexico | Qaim 1998 | E | ex ante | 6.68–10.72 | | | | | 69.6–139.84 |
| Virus-resistant PVX-PVY-PLRV | | | E | ex ante | 34.98–42.98 | | | | | 390.9–559.38 |
| SWEET POTATOES | | | | | | | | | | |
| Virus Resistant Sweet Potatoes | Kenya | Qaim 1998 | E | ex-ante | 7.8–16.33 | | | | | 42.31–101.12 |

Source: Compiled by authors.

Note: Under "study type," A denotes field trial-conventional versus transgenic varieties; B denotes farmer survey-side-by-side comparisons; C denotes field trial-side-by-side, on-farm comparisons; D denotes paired field comparisons; E denotes expert opinion; F denotes other means of comparison. Superscript “a” denotes the 6 studies that were omitted from the analysis, as discussed in the beginning of section 5.

LIST OF EPTD DISCUSSION PAPERS

01 *Sustainable Agricultural Development Strategies in Fragile Lands*, by Sara J. Scherr and Peter B.R. Hazell, June 1994.

02 *Confronting the Environmental Consequences of the Green Revolution in Asia*, by Prabhu L. Pingali and Mark W. Rosegrant, August 1994.

*03* *Infrastructure and Technology Constraints to Agricultural Development in the Humid and Subhumid Tropics of Africa,* by Dunstan S.C. Spencer, August 1994.

04 *Water Markets in Pakistan: Participation and Productivity*, by Ruth Meinzen-Dick and Martha Sullins, September 1994.

05 *The Impact of Technical Change in Agriculture on Human Fertility: District-level Evidence From India,* by Stephen A. Vosti, Julie Witcover, and Michael Lipton, October 1994.

06 *Reforming Water Allocation Policy Through Markets in Tradable Water Rights: Lessons from Chile, Mexico, and California,* by Mark W. Rosegrant and Renato Gazri S, October 1994.

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