The Economics of Genetically Modified Crops

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Annu. Rev. Resour. Econ. 2009. 1:665–93

The *Annual Review of Resource Economics* is online at resource.annualreviews.org

This article's doi:
10.1146/annurev.resource.050708.144203

1941-1340/09/1010-0665$20.00

Key Words

agricultural biotechnology, consumer acceptance, impacts, regulation, technology adoption

Abstract

Genetically modified (GM) crops have been used commercially for more than 10 years. Available impact studies of insect-resistant and herbicide-tolerant crops show that these technologies are beneficial to farmers and consumers, producing large aggregate welfare gains as well as positive effects for the environment and human health. The advantages of future applications could even be much bigger. Given a conducive institutional framework, GM crops can contribute significantly to global food security and poverty reduction. Nonetheless, widespread public reservations have led to a complex system of regulations. Overregulation has become a real threat for the further development and use of GM crops. The costs in terms of foregone benefits may be large, especially for developing countries. Economics research has an important role to play in designing efficient regulatory mechanisms and agricultural innovation systems.

1. INTRODUCTION

A genetically modified (GM) crop is a plant used for agricultural purposes into which one or several genes coding for desirable traits have been inserted through the process of genetic engineering. These genes may stem not only from the same or other plant species, but also from organisms totally unrelated to the recipient crop. The basic techniques of plant genetic engineering were developed in the early 1980s, and the first GM crops became commercially available in the mid-1990s. Since then, GM crop adoption has increased rapidly. In 2008, GM crops were being grown on 9% of the global arable land (James 2008).

The crop traits targeted through genetic engineering are not completely different from those pursued by conventional breeding. However, because genetic engineering allows for the direct gene transfer across species boundaries, some traits that were previously difficult or impossible to breed can now be developed with relative ease. Three categories of GM traits can be distinguished: First-generation GM crops involve improvements in agronomic traits, such as better resistance to pests and diseases. Second-generation GM crops involve enhanced quality traits, such as higher nutrient contents of food products. Third-generation crops are plants designed to produce special substances for pharmaceutical or industrial purposes.

The potentials of GM crops are manifold. Against the background of a dwindling natural resource base, productivity increases in global agriculture are important to ensure sufficient availability of food and other raw materials for a growing population (von Braun 2007). GM crops can also bring about environmental benefits. Furthermore, new seed technologies have, in the past, played an important role for rural income growth and poverty alleviation in developing countries (e.g., Hazell & Ramasamy 1991, Fan et al. 2005). These effects are also expected for GM crops (FAO 2004). Finally, nutritionally enhanced crops could help improve the health status of consumers (e.g., Bouis 2007, Unnevehr et al. 2007).

In spite of these potentials, the development and use of GM crops have aroused significant opposition. Public reservations are particularly strong in Europe, but they have also spilled over to other countries and regions through trade regulations, public media, and outreach efforts of antibiotech lobbying groups (e.g., Pinstrup-Andersen & Schioler 2001, Miller & Conko 2004, Herring 2007, Paarlberg 2008). The major concerns are related to potential environmental and health risks, but there are also fears about adverse social implications (e.g., Altieri 2001, Friends of the Earth 2008). For instance, some believe that GM technology could undermine traditional knowledge systems in developing countries. Given the increasing privatization of crop improvement research and proliferation of intellectual property rights (IPRs), there are also concerns about the potential monopolization of seed markets and exploitation of smallholder farmers (e.g., Sharma 2004).

Because GM crops are associated with new potentials and issues, their emergence has also triggered substantial research dealing with economic and policy aspects. This article reviews the available research on the economics of GM crops. Section 2 gives a brief overview of the status of commercialized GM crops and expected trends for the future. Then, work related to the analysis of impacts at the micro and macro level is discussed. Whereas Sections 3 and 4 address impacts of first-generation GM applications, Section 5 refers to second-generation crops from an ex ante perspective. Sections 6 and 7 focus on consumer acceptance and the economics of regulation, including aspects of biosafety as well as food labeling and IPRs. In the concluding section, policy and research implications are discussed.

2. STATUS OF GM CROPS

2.1. Commercialized GM Crops

The commercial application of GM crops began in the mid-1990s. Since then, the technology has spread rapidly around the world, both in industrialized and developing countries (**Figure 1**). In 2008, GM crops were being grown on 125 million ha in 25 countries. The countries with the biggest share of the GM crop area were the United States (50%), Argentina (17%), Brazil (13%), India (6%), Canada (6%), and China (3%) (James 2008). Strikingly, among the countries of the European Union (EU), only Spain grows GM crops on a significant scale. Although a few other EU countries have approved individual GM technologies, the commercial area is still negligible, because of public-acceptance problems and unfavorable regulatory frameworks.

In spite of the widespread international use of GM crops, the portfolio of available crop-trait combinations is still very limited. At present, only a few first-generation technologies have been commercialized. The dominant technology is herbicide tolerance (HT) in soybeans, which made up 53% of the global GM crop area in 2008. HT soybeans are currently grown mostly in the United States, Argentina, Brazil, and other South American countries. This technology accounts for 70% of worldwide soybean production.

GM maize is the second-most dominant crop and covered 30% of the global GM area and 24% of total maize production in 2008 (James 2008). GM maize involves HT and insect resistance, partly as separate and partly also as stacked technologies. Insect resistance is based on different genes from the soil bacterium *Bacillus thuringiensis* (Bt). These Bt genes control the European corn borer, the corn rootworm, and different stemborers (Romeis et al. 2008). Bt maize is grown mostly in North and South America, but it is also planted to a significant extent in South Africa and the Philippines.

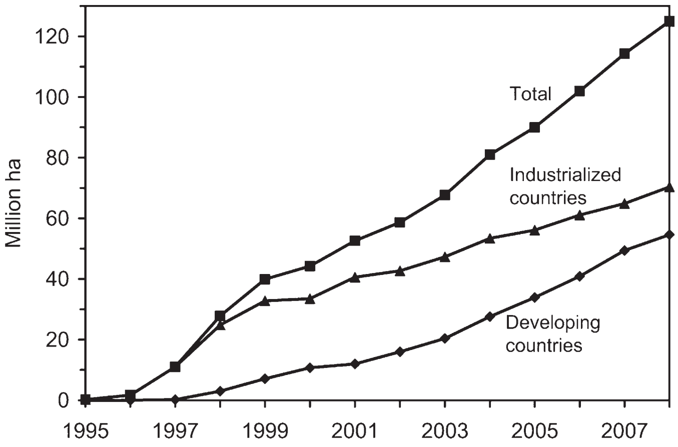

Figure 1

Development of the global area using genetically modified crops (1995–2008).
Source: James (2008).

GM crops with significant area shares also include cotton and canola. Bt cotton with resistance to bollworms and budworms is particularly relevant in developing countries. In 2008, India had the largest Bt cotton area with 7.6 million ha, followed by China with 3.8 million ha. South Africa, Argentina, Mexico, and a few other countries use this technology as well. In the United States, Bt and HT cotton are employed, partly with stacked genes. Until now, HT canola was grown mostly in Canada and the United States. A few other GM crops, including HT alfalfa and sugarbeet as well as virus-resistant papaya and squash, have been approved in individual countries, so far covering only relatively small areas.

2.2. GM Crops in the Pipeline

A couple of GM technologies previously developed for food crops either were never commercialized or were withdrawn from the market because of consumer-acceptance and marketing problems. Examples include Bt and virus-resistant potato as well as HT wheat. Yet, such technologies may be reintroduced, should public acceptance improve. A number of other GM crop technologies that provide insect resistance or HT are ready to be commercialized. For instance, Bt rice has been field tested extensively in China and other countries (Huang et al. 2005, Cohen et al. 2008). Different Bt vegetables—including eggplant, cauliflower, and cabbage—are likely to be commercialized soon in India and other countries in Asia and Africa (Krishna & Qaim 2007, Shelton et al. 2008). HT rice is also in a relatively advanced phase within the research and development (R&D) pipeline (Hareau et al. 2006).

Other first-generation GM technologies that are being developed include fungal, bacterial, and virus resistance in major cereal as well as root and tuber crops (Halford 2006). Their market introduction can be expected in the short to medium run. Plant tolerance to abiotic stress—such as drought, heat, and salt—is also being worked on intensively. Yet, because the underlying genetic mechanisms are complex, the work is at a more basic level, so significant commercial releases can be expected only in the medium run (Herdt 2006, Ramasamy et al. 2007).

Second-generation GM technologies in the pipeline include product quality improvements for nutrition and industrial purposes. Examples are oilseeds with improved fatty acid profiles; high-amylose maize; staple foods with enhanced contents of essential amino acids, minerals, and vitamins; and GM functional foods with diverse health benefits (Jefferson-Moore & Traxler 2005, Pew Initiative on Food and Biotechnology 2007).

Enhancing food crops with higher nutrient contents through conventional or GM breeding is also called biofortification. A well-known example of a GM biofortified crop is Golden Rice, which contains significant amounts of provitamin A. Golden Rice could become commercially available in some Asian countries by 2012 (Stein et al. 2006, Potrykus 2008). Other biofortification projects include the development of GM sorghum, cassava, banana, and rice enhanced with multiple nutrients (Qaim et al. 2007). Such crops may become commercially available over the next 5–10 years.

Third-generation GM crops involve molecular farming where the crop is used to produce either pharmaceuticals such as monoclonal antibodies and vaccines or industrial products such as enzymes and biodegradable plastics (Moschini 2006, Halford 2006). Although concepts have been proven for a number of these technologies, product development and regulatory aspects are even more complex than they are for first- and second-generation crops. Substances produced in the plants must be guaranteed not to enter the regular food chain with a zero-tolerance threshold. Therefore, plants that are not used for food and feed purposes will likely be chosen for product development, or approvals for third-generation GM crops will be given for use under contained conditions only. In either case, this brief overview reveals that the GM crops available so far represent only a very small fraction of the large future potentials of plant genetic engineering.

3. MICROLEVEL IMPACTS OF FIRST-GENERATION GM CROPS

Because HT and insect-resistant Bt crops have already been used for a number of years, numerous microlevel impact studies have been carried out in different countries. Many such studies are based on random sample surveys, comparing the performance of adopters and nonadopters of GM crops (Kalaitzandonakes 2003, Naseem & Pray 2004, Qaim 2005, Gandhi & Namboodiri 2006). However, such with-without comparisons can be associated with a selectivity bias. On the one hand, if adopting farmers are more skillful than their nonadopting counterparts, the net technological impacts may be overestimated, because the group of adopters may show better performance even without GM technology. On the other hand, if the technology is adopted only by farmers under specific conditions, net impacts may be underestimated. For instance, Bt technology is expected to be particularly beneficial in high pest pressure environments. Therefore, simply comparing the productivity of adopters in high pest pressure environments with that of nonadopters in low pest pressure environments would lead to a downward bias in impact assessment.

Different approaches have been used to reduce a potential selectivity bias. For instance, some authors have observed developments over time, involving several rounds of data collection (e.g., Pray et al. 2002, Sadashivappa & Qaim 2009). Others have combined survey data of GM farmers with calculations of what would have been without technology adoption (e.g., Gianessi et al. 2002, Brookes & Barfoot 2008). In addition, within-farm comparisons have been made in situations where adopting farmers continued to use conventional crops on part of their land (e.g., Qaim & de Janvry 2005). Econometric approaches to deal with selectivity issues are explained below.

3.1. Farm-Level Impacts of HT Crops

HT crops are tolerant to certain broad-spectrum herbicides such as glyphosate and glufosinate, which are more effective, less toxic, and usually cheaper than selective herbicides. Accordingly, farmers who adopt HT technology benefit in terms of lower herbicide expenditures. Total herbicide quantities applied were reduced in some situations, but not in others. In Argentina, herbicide quantities were increased significantly (Qaim & Traxler 2005), in large part owing to the fact that herbicide sprays were substituted for tillage. In Argentina, the share of soybean farmers using no-till doubled to almost 90% since the introduction of HT technology (Trigo & Cap 2006), whereas in the United States and Canada, no-till practices expanded through HT adoption (Kalaitzandonakes 2003, Fernandez-Cornejo & Caswell 2006). In terms of the yields achieved, no significant difference between HT and conventional crops is seen in most cases. Only in a few examples when certain weeds were difficult to control with selective herbicides did the adoption of HT and the switch to broad-spectrum herbicides result in better weed control and higher crop yields. These include HT soybeans in Romania and HT maize in Argentina (Brookes & Barfoot 2008).

Overall, HT technology reduces the cost of production through lower expenditures for herbicides, labor, machinery, and fuel. Yet, because HT crops were developed and commercialized by private companies, a technology fee is charged on seeds, which varies among crops as well as countries. Several early studies for HT soybeans in the United States showed that the fee was of a similar magnitude or sometimes higher than the average cost reduction, so that gross margin effects were small or partly negative (e.g., Duffy 2001, Fernandez-Cornejo et al. 2002). Comparable results were also obtained for HT cotton and HT canola in the United States and Canada (Fulton & Keyowski 1999, Marra et al. 2002, Phillips 2003, Naseem & Pray 2004). The main reasons for farmers in such situations to continue using HT technologies were easier weed control and savings in terms of management time. Fernandez-Cornejo et al. (2005) showed that the saved management time for U.S. soybean farmers translated in part into higher off-farm incomes. Moreover, farmers are heterogeneous, such that many adopters have benefited in spite of zero or negative mean gross margin effects. The average farm-level profits seem to increase over time, partly as a result of seed-price adjustments and farmer-learning effects.

In South American countries, the average gross margin effects of HT crops, especially HT soybeans, are larger than in North America (Trigo & Cap 2006). While the agronomic advantages are similar, the fee charged on seeds is lower, as HT technology is not patented there. Many soybean farmers in South America use farm-saved GM seeds. Qaim & Traxler (2005) showed that the average gross margin gains through HT soybean adoption are in a magnitude of more than \$20 per ha for Argentina.

3.2. Farm-Level Impacts of Bt Crops

Insect-resistant Bt crops have different effects than do HT crops. Bt crops produce proteins that are toxic to larvae of some lepidopteran and coleopteran insect species. Therefore, Bt is a pest-control agent that can be used as a substitute for chemical insecticides. Following Lichtenberg & Zilberman (1986) and Zilberman et al. (2004), this can be expressed in a damage-control framework:

$$Y = F(x)[1 - D(z, Bt; N)],$$

where Y is the effective crop yield, and $F(\cdot)$is potential yield without insect damage, which depends on variable inputs, x. $D(\cdot)$is the damage function determining the fraction of potential output being lost to insect pests; it can take values in the 0–1 interval. Crop losses depend on exogenous pest pressure, N, and they can be reduced through the application of chemical insecticides, z, and/or the use of Bt technology. If pest pressure is high and farmers use a lot of chemical insecticides in the conventional crop, Bt adoption should lead to substantial insecticide reductions.[1] However, Bt technology can also impact effective crop yields. Even though the Bt gene does not affect potential yield, $F(\cdot)$, it can lead to a reduction in crop losses, $D(\cdot)$, when there is previously uncontrolled pest damage, thus leading to a higher Y.

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[1] Pemsl et al. (2008) pointed out that natural pest-control agents such as beneficial insects could also reduce crop losses but that these are often suppressed through chemical insecticides. Therefore, even without Bt, a reduction in chemical insecticides may be possible in specific situations. However, compared with chemical insecticides, Bt is much less harmful to beneficial insects (Shelton et al. 2009).

Insecticide reduction and yield effects are closely related: Farmers who use small amounts of insecticides in their conventional crop in spite of high pest pressure will realize a sizeable yield effect through Bt adoption, whereas the insecticide reduction effect will dominate in situations when farmers initially use higher amounts of chemical inputs. The same principles also hold for other pest-resistant GM crops. In general, yield effects will be more pronounced in developing rather than in developed countries, because pest pressure is often higher in the tropics and subtropics and resource-poor farmers face more severe constraints in chemical pest control (Qaim & Zilberman 2003).

3.2.1. Empirical evidence. The Bt-insecticide-yield linkages are diagrammed in **Figure 2** using field trial data with Bt cotton in India. As shown, Bt does not completely eliminate the need for insecticide sprays because some crop damage still occurs when the technology is used. The reason is that Bt toxins are very specific to certain pest species, whereas other insect pests, especially sucking pests, remain unaffected.

What do the agronomic impacts look like under practical farmer conditions? **Table 1** confirms that both insecticide-reducing and yield-increasing effects can be observed internationally. Yield effects of Bt cotton are highest in Argentina and India. For Argentina, the explanation is simple: Conventional cotton farmers underutilize chemical insecticides, so that insect pests are not effectively controlled (Qaim & de Janvry 2005). In India, however, insecticide use in conventional cotton is much higher (Qaim et al. 2006). This suggests that factors other than insecticide quantity influence damage control in conventional cotton and, thus, the yield effects of Bt technology. These factors include insecticide quality, insecticide resistance, and the correct choice of products and timing of sprays.

For Bt maize, similar effects are observable, albeit generally at a lower magnitude (**Table 1**). Except for Spain, where the percentage reduction in insecticide use is large, the more important result of the use of Bt maize is an increase in effective yields. In the United States, for instance, Bt maize is used mainly against the European corn borer, which is not

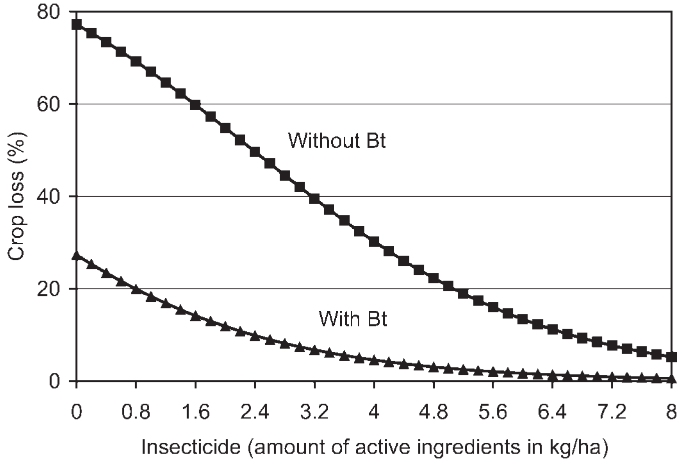

Figure 2

Relationship between insecticide use and cotton crop losses with and without Bt in India.
Source: Qaim & Zilberman (2003).

Table 1 Average farm-level agronomic and economic effects of Bt crops

Country	Insecticide reduction (%)	Increase in effective yield (%)	Increase in gross margin (US$/ha)	Reference(s)
Bt cotton				
Argentina	47	33	23	Qaim & de Janvry 2003, 2005
Australia	48	0	66	Fitt 2003
China	65	24	470	Pray et al. 2002
India	41	37	135	Qaim et al. 2006, Sadashivappa & Qaim 2009
Mexico	77	9	295	Traxler et al. 2003
South Africa	33	22	91	Thirtle et al. 2003, Gouse et al. 2004
United States	36	10	58	Falck-Zepeda et al. 2000b, Carpenter et al. 2002
Bt maize				
Argentina	0	9	20	Brookes & Barfoot 2005
Philippines	5	34	53	Brookes & Barfoot 2005, Yorobe & Quicoy 2006
South Africa	10	11	42	Brookes & Barfoot 2005, Gouse et al. 2006
Spain	63	6	70	Gómez-Barbero et al. 2008
United States	8	5	12	Naseem & Pray 2004, Fernandez-Cornejo & Li 2005

often controlled by chemical means (Carpenter et al. 2002).[2] In Argentina and South Africa, mean yield effects are higher because pest pressure is more severe than it is in temperate climates. The average yield gain of 11% shown in **Table 1** for South Africa refers to large commercial farms. These farms have been growing yellow Bt maize hybrids for several years. Gouse et al. (2006) analyzed on-farm trials that were carried out with smallholder farmers and white Bt maize hybrids in South Africa. They found average yield gains of 32% on Bt plots. In the Philippines, average yield advantages are 34%.

Preliminary evidence based on field-trial observations also exists for other Bt crops. Huang et al. (2005) observed high insecticide reductions but relatively small yield effects for Bt rice in China, whereas Krishna & Qaim (2008b) reported significant insecticide and yield effects for Bt eggplant in India.

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[2] More recently, a different Bt maize technology has been commercialized in the United States to control the corn rootworm complex, against which significant amounts of chemical insecticides are used in conventional agriculture. However, representative studies on the impacts of this new Bt maize technology under farmer conditions are not available.

3.2.2. Econometric estimates. Econometric analyses with different model specifications confirm the net insecticide-reducing and yield-increasing effects of Bt technology. For Bt maize, Fernandez-Cornejo & Li (2005) provided estimates for the United States, and Yorobe & Quicoy (2006) did so for the Philippines. More studies are available for Bt cotton: Huang et al. (2002a) employed an insecticide-use model and a production function with a damage-control specification to estimate the effects in China. A similar analysis was done by Qaim & de Janvry (2005) in Argentina. Bennett et al. (2006) estimated Cobb-Douglas-type production functions for a sample of farmers in India.

Qaim et al. (2006) also estimated productivity effects of Bt cotton in India, differentiating between Bt gene and germplasm effects. They showed that part of the impact variability observed in India during the first years of adoption was due to the incorporation of the Bt gene in only a few cotton varieties that were not suitable for all locations. In such situations, a yield drift can be observed; that is, the positive Bt gene effect is counteracted by a negative germplasm effect. This underlines the finding that the benefits of GM can be fully realized only when the technology is inserted into a number of locally adapted varieties.

Thirtle et al. (2003) used a stochastic frontier approach with data from farmers in South Africa to show that Bt adoption helps to increase the technical efficiency of cotton production in the small-farm sector. Kambhampati et al. (2006) did a similar analysis for India. Many of these econometric analyses used instrumental variable approaches to avoid or reduce selectivity issues and problems of endogeneity. One study by Crost et al. (2007) also used panel data techniques for the estimation of Bt productivity effects.

3.2.3. Gross margin effects. The gross margin effects of Bt technologies are also shown in **Table 1**. In all countries noted, Bt-adopting farmers benefit; that is, the economic advantages associated with insecticide savings and higher effective yields more than outweigh the technology fee charged on GM seeds. The absolute gains differ remarkably among countries and crops. On average, the gross margin gains are higher for Bt cotton than for Bt maize, and they are also higher in developing as opposed to developed countries. In addition to agroecological and socioeconomic differences, the GM seed costs are often lower in developing countries, owing to weaker IPRs, seed reproduction by farmers, subsidies, or other types of government price interventions (Basu & Qaim 2007, Sadashivappa & Qaim 2009).

Agricultural policies are also partly responsible for the different gross margin effects. For instance, in the United States, China, and Mexico, the cotton sector is subsidized, which encourages intensive production schemes and high overall yields. The situation is similar for maize in Spain. By contrast, Argentinean farmers are not subsidized; instead, they face world-market prices. Especially for cotton, world-market prices have been declining over the past 10 years, thus eroding the economic benefits resulting from technological yield gains. Furthermore, within countries, farmer conditions are heterogeneous so that the effects are variable (Qaim et al. 2006, Pemsl & Waibel 2007).

3.3. Poverty and Distribution Effects

Seventy-five percent of all poor people in the world are smallholder farmers or rural laborers. Therefore, GM crops may also have important implications for poverty and income distribution in developing countries. If only rich farmers were to benefit, inequality would increase. Yet, if resource-poor farmers could access GM crops suitable for their situations, the poverty and equity effects may be positive. Apart from technological characteristics, this also depends on the institutional setting at national and local levels (Qaim et al. 2000, Evenson et al. 2002). For instance, strong IPRs and high seed prices as well as information, credit, and infrastructure constraints can hinder poor farmers' proper access to GM seeds, even if the underlying technology is suitable for smallholder agriculture (e.g., Qaim & de Janvry 2003, Thirtle et al. 2003, Qaim 2005, Edmeades & Smale 2006).

So far, HT crops have not been widely adopted in the small-farm sector. Smallholders often weed manually, so that HT crops are inappropriate, unless labor shortages or weeds that are difficult to control justify conversion to chemical practices. The situation is very different for Bt crops. Especially in China, India, and South Africa, Bt cotton is often grown by farms with less than 3 ha of land (Huang et al. 2002a,b; Qaim et al. 2008). In South Africa, many smallholders grow Bt white maize as their staple food (Gouse et al. 2006). Several studies show that Bt technology advantages for small-scale farmers are of a similar magnitude as those of larger-scale producers. In some cases, the advantages can be even greater (Pray et al. 2001, Morse et al. 2004, Qaim et al. 2008).[3]

However, few studies exist that have analyzed wider socioeconomic outcomes, including effects on rural employment and household incomes. This dearth of broader microlevel research may be the reason for the ongoing controversy surrounding the poverty and rural development implications of GM crops. Subramanian & Qaim (2009a,b) provide the first comprehensive work in this direction. Building on a village social accounting matrix and multiplier model, they examined direct and indirect effects of Bt cotton adoption in India. Their results show that the technology is employment generating, especially for hired female agricultural laborers, which is due to significantly higher yields in need of harvesting. The technology also generates employment in other sectors linked to cotton production, e.g., trade and services.

Simulated impacts on household incomes are shown in **Figure 3**. Each additional hectare of Bt cotton produces 82% higher aggregate incomes than are obtained from conventional cotton, implying a remarkable gain in overall economic welfare through technology adoption in India. For landless households, the positive income effects are relatively small. More female employment for cotton harvesting is counteracted by less male employment for spraying operations. However, all types of farm households—including those below the poverty line—benefit considerably more from Bt than from conventional cotton. These findings demonstrate that GM crops can contribute significantly to poverty reduction and rural development, when they are suited to the small-farm sector and embedded in a conducive institutional environment.

3.4. Environmental and Health Effects

In addition to the economic and social impacts of GM crops, there are also environmental and health implications. In the public debate, potential environmental risks, such as undesirable gene flow or impacts on nontarget organisms, are often in the fore. Food safety concerns are also raised. Shelton et al. (2009), Weaver & Morris (2005), and

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[3] Especially for India, biotech critics still report that Bt cotton ruins smallholder farmers. However, such reports do not build on representative data (Qaim et al. 2006, 2008). Gruère et al. (2008) showed that the occasional claim of a link between Bt cotton adoption and farmer suicides cannot be substantiated.

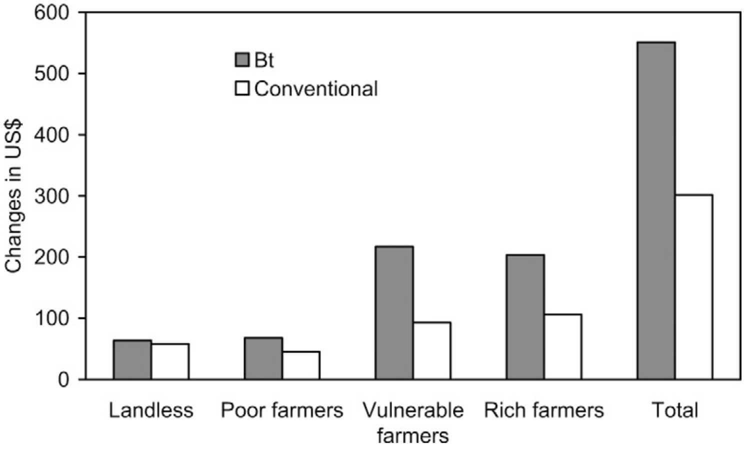

Figure 3

Household income effects of Bt cotton compared with conventional cotton in India. The results are based on simulations with a social accounting matrix and multiplier model for a typical cotton-growing village in the Indian state of Maharashtra. Two simulations were run, both considering an expansion in the village cotton area by 1 ha. The first scenario assumes that the additional hectare is cultivated with Bt cotton, whereas the second assumes that it is cultivated with conventional cotton. Accordingly, differences between the two scenarios can be interpreted as net impacts of Bt technology adoption. Adapted from Subramanian & Qaim (2009a).

Bradford et al. (2005) have reviewed such risks, concluding that most are not specific to the technique of genetic modification but would be present for any conventionally produced crops with the same heritable traits. Although potential risks need to be further analyzed and managed, GM crops can also induce substantial environmental and health benefits.

3.4.1. Environmental benefits. Adoption of HT crops does not lead to reductions in herbicide quantities in most cases, but selective herbicides, which are often relatively toxic to the environment, are substituted by much less toxic broad-spectrum herbicides. Moreover, tillage operations are cut and no-till practices expanded, helping to reduce soil erosion, fuel use, and greenhouse gas emissions (Qaim & Traxler 2005, Brookes & Barfoot 2008).

For Bt crops, the main environmental benefits are related to reductions in chemical insecticide applications. Reductions in pesticide use have been particularly significant in cotton, the most pesticide-consuming crop worldwide. Brookes & Barfoot (2008) estimated that between 1996 and 2006 Bt cotton was responsible for global savings of 128 million kg of pesticide active ingredients, reducing the environmental impact of total cotton pesticides by 25%. **Figure 4** shows that Bt adoption leads to overproportional reductions in the most toxic insecticides.

In the first years of Bt crop deployment, it was predicted that insect populations would soon develop Bt resistance, which would undermine the technology's effectiveness and lead to declining insecticide reductions over time. However, until now, Bt resistance has not been observed under field conditions, which may be due to successful resistance management strategies, such as the planting of non-Bt refuges (Hurley et al. 2001, Bates et al. 2005). In countries where no such strategies are implemented, Bt resistance has also not been reported. However, other factors can lead to changes in Bt effects over time.

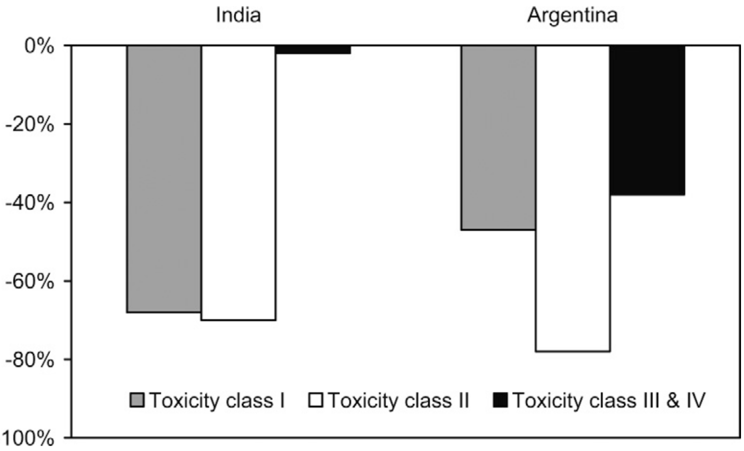

Figure 4

Insecticide reductions through Bt cotton by toxicity class. Results are based on within-farm comparisons obtained from surveys in different cotton-growing regions of India and Argentina. Following the international classification of pesticides, toxicity class I comprises the most toxic products, whereas toxicity class IV comprises the least toxic products. Based on data from Qaim & Zilberman (2003), Qaim et al. (2006), and Qaim & de Janvry (2005).

In China, for instance, insecticide applications increased again after several years of Bt cotton use, in spite of the absence of Bt resistance. Wang et al. (2006) attributed this to secondary pests, which may have become more important through the Bt-induced reduction in broad-spectrum insecticides. Their analysis, however, was based on only one year of observations with increased insecticide applications, making conclusive statements premature (Hu et al. 2006). Using data collected over a period of five years, Sadashivappa & Qaim (2009) did not find any evidence of secondary-pest outbreaks in India.

GM crops may also help preserve agrobiodiversity. Conventional breeding leads to new crop varieties. If a particular new variety produces a large productivity gain, it may spread widely, potentially replacing a large number of older varieties and landraces. This occurred to some extent during the Green Revolution in Asia (Cooper et al. 2005). Developing additional conventional varieties with similar characteristics can be a long and costly process. In contrast, the development of GM traits through genetic engineering can be backcrossed at moderate costs into numerous varieties.[4] Therefore, instead of replacing local varieties, GM versions of these varieties can be made available. Indeed, in most countries where GM technologies have been commercialized, a large number of varieties carrying specific GM traits can be observed (e.g., Qaim 2005, Trigo & Cap 2006, Qaim et al. 2008). More than a technical question, the impact of GM technologies on varietal diversity depends on the design of IPR and biosafety policies, breeding capacities, and other institutional conditions (Zilberman et al. 2007).

3.4.2. Health benefits. GM crops, especially Bt crops, are also associated with health benefits. Direct health advantages for farmers are a result of less insecticide exposure

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[4] This is also one reason why genetic engineering is a complementary tool and not a substitute for conventional breeding. GM traits will always have to be incorporated into locally adjusted germplasm.

during spraying operations. Often, the health hazards for farmers applying pesticides are greater in developing as opposed to developed countries because environmental and health regulations are more lax, most pesticides are applied manually, and farmers are less educated and less informed about negative side effects. Pray et al. (2001) and Huang et al. (2003) showed that the frequency of pesticide poisonings was significantly lower among Bt cotton adopters than among nonadopters in China. Hossain et al. (2004) used econometric models to establish that this observation is causally related to Bt technology. Bennett et al. (2003) made the same observation for Bt cotton in South Africa, and there is first evidence that similar effects can also be expected for other Bt crops in smallholder agriculture, such as Bt rice in China (Huang et al. 2005, 2008). Using econometric estimates and a cost-of-illness approach, Krishna & Qaim (2008b) projected that Bt eggplant in India may produce farmer health benefits worth approximately $4 million per year.

For consumers, Bt crops can yield health benefits through lower pesticide residues in food and water. Furthermore, in a variety of field studies, Bt maize was shown to contain significantly lower levels of certain mycotoxins, which can cause cancer and other diseases in humans (Wu 2006). Especially in maize, insect damage contributes significantly to mycotoxin contamination. In the United States and other developed countries, maize is carefully inspected, so lower mycotoxin levels may be most responsible for reducing the costs of testing and grading. But in many developing countries, strict mycotoxin inspections are uncommon. In such situations, Bt technology could contribute to lowering the total health burden (Wu 2006, Qaim et al. 2008).

4. MACROLEVEL IMPACTS OF FIRST-GENERATION GM CROPS

Numerous studies using macrolevel economic surplus models have analyzed the broader welfare effects of GM crops. When the market of only one single crop is considered, partial equilibrium models are used, whereas general equilibrium models are employed when indirect effects and spillovers to other markets and sectors are also of interest.

4.1. Partial Equilibrium Approaches

Whenever new crop technologies are adopted on a large scale, the productivity increase will cause the crop's supply curve to shift downward, leading to a change in producer and consumer surplus (Alston et al. 1995). Because most GM technologies currently available have been commercialized by the private sector, technology rents accrued by innovating companies need to be considered (Moschini & Lapan 1997).

Price et al. (2003) estimated that in the late 1990s Bt cotton generated a total annual economic surplus gain of approximately $164 million in the United States, of which 37% was captured by farmers, 18% by consumers, and 45% by the innovating companies. Falck-Zepeda et al. (2000b) also reported similar results. Because Bt cotton adoption in the United States has increased since then, absolute surplus gains are higher today, but relative surplus distribution remains approximately the same (Fernandez-Cornejo & Caswell 2006).

For Bt cotton in China, Pray et al. (2001) estimated economic surplus gains of approximately $140 million in 1999, with only 1.5% going to the innovating companies and the rest captured by farmers. IPR protection in China is weak, and use of farm-saved Bt cottonseeds is widespread. Under these conditions, it is difficult for companies to capture innovation rents. Cotton consumers did not benefit in 1999 because the government controlled output markets, thus preventing a price decrease. Recently, markets have been liberalized, so Chinese consumers now benefit from Bt cotton technology. In India, Bt cotton surplus gains were projected at $315 million for 2005 (Qaim 2003). Because cotton prices there are not fully liberalized, consumer benefits were not considered. Farmers capture two thirds of the overall surplus gains; the rest accrues to biotech and seed companies. Bt cotton in India is commercialized in hybrids, so use of farm-saved seeds is low. Thus, the private sector innovation rent is higher than in China.

For Bt maize in the United States, Wu (2002) estimated a total surplus gain of $334 million in 2001. Approximately half of the gain accrued to producers, followed by industry profits (31%). The consumer share was relatively small. For Bt maize in Spain, Demont & Tollens (2004) calculated welfare gains of approximately $2 million in 2003, of which 60% went to farmers and 40% to seed companies. The relatively low absolute gain is due to the fact that Bt maize in 2003 covered only an area of approximately 25,000 ha. Similar effects were shown during the early years of Bt maize adoption in the Philippines (Yorobe & Quicoy 2006).

A number of studies have examined the partial equilibrium effects of HT soybeans (e.g., Moschini et al. 2000, Falck-Zepeda et al. 2000a, Qaim & Traxler 2005). Most of these studies use multiregion models. Worldwide welfare gains of HT soybeans were on the order of US$1 billion in the late 1990s. Gains have grown since then as a result of increased adoption. At the global level, downstream sectors and consumers are the main beneficiaries, capturing more than 50% of surplus gains. The effects vary strongly by country, however. Within the United States, farmers capture approximately 20% of the national welfare gains versus almost 60% accruing to Monsanto as the innovating company. By contrast, in Argentina, the farmer surplus share is 90%. These differences are largely due to different levels of IPR protection (Qaim & Traxler 2005).

In addition to such ex post studies, ex ante studies for GM crops have also been carried out in different countries. Examples include analyses for Bt maize and different HT crops in the EU (Demont et al. 2004, 2008), HT rice in Uruguay (Hareau et al. 2006), Bt eggplant in India (Krishna & Qaim 2008b), drought-tolerant rice in India and Bangladesh (Ramasamy et al. 2007), and virus- and insect-resistant sweet potato in Kenya (Qaim 2001). These ex ante studies confirm that GM crops can bring about sizeable welfare gains, with distributional effects dependent on IPRs and other institutional conditions.

4.2. General Equilibrium Approaches

Many of the available general equilibrium studies use the multiregion computable general equilibrium (CGE) model and associated database of the Global Trade Analysis Project (Hertel 1997). This model captures the vertical and horizontal linkages between markets within regions and between regions via bilateral trade flows. The results of several global impact studies are summarized in **Table 2**.

Bt cotton adoption entails global welfare gains in the range of $0.7–1.8 billion per year. The differences across studies partly reflect the use of different versions of the basic model. More importantly, however, the assumed technology adoption rates in different regions matter. Because Bt adoption continues to increase, the aggregate welfare gains are increasing too. Most CGE studies for Bt cotton to date found the biggest regional welfare effects occurred in China (e.g., Huang et al. 2004, Frisvold & Reeves 2007), but India, where the technology was commercialized later, has been catching up rapidly. Anderson et al. (2008)

Table 2 Projected global welfare gains from GM crops (CGE model results)[a]

Reference	Crop	Year of study	Annual welfare gain (US$)
Frisvold & Reeves (2007)	Bt cotton	2005	1.4 billion
Elbehri & MacDonald (2004)	Bt cotton	2001	1.8 billion
Anderson & Yao (2003)	Bt cotton	2005	1.4 billion
Anderson et al. (2008)	Bt cotton	2001	0.7 billion
Nielsen & Anderson (2001)	GM oilseeds and maize	—	9.9 million
Anderson & Yao (2003)	GM soybean and maize	—	7.0 billion
Hareau et al. (2005)	Bt rice	—	2.2 billion
Hareau et al. (2005)	Drought-tolerant rice	—	2.5 billion
Hareau et al. (2005)	HT rice	—	2.1 billion
Anderson & Yao (2003)	GM rice	—	2.0 billion

[a]Abbreviations: CGE, computable general equilibrium; GM, genetically modified; HT, herbicide tolerant.

estimate that widespread adoption of Bt cotton in India and other countries of South Asia will result in additional regional welfare gains on the order of $1 billion per year.

Larger international markets result in bigger effects for GM oilseeds and maize. With widespread international adoption of HT and insect resistance in these crops, annual welfare gains could be approximately $10 billion (Nielsen & Anderson 2001). A ban on production and imports by the EU, however, could reduce these global gains by two thirds, because of foregone benefits for domestic consumers and the far-reaching influence of EU policies on international trade flows and production decisions in exporting regions (Tothova & Oehmke 2005).

For GM rice, large global welfare gains are projected as well. For other rice technologies, such as Bt, HT, and drought tolerance, and assuming moderate adoption levels in rice-producing regions, Hareau et al. (2005) estimated global welfare gains of $2.1–2.5 billion per year, with India and China gaining the most. Huang et al. (2004) projected that the welfare gains in China alone could reach over $4 billion when different first-generation GM rice technologies are widely adopted. The studies available to date provide lower bound estimates of the global welfare effects of GM crops, because positive environmental and health externalities have not been properly quantified.

5. POTENTIAL IMPACTS OF SECOND-GENERATION GM CROPS

First-generation GM crops involve direct productivity and income effects, which can be evaluated at the micro level and then integrated into macrolevel modeling approaches. Second-generation crops, which involve enhanced quality attributes, must be evaluated differently. Quality improvements generally lead to a marginal utility increase and a higher willingness to pay (WTP) among consumers. In a market model, this can be represented as an upward shift in the crop's demand function. There are no ex post impact studies available for second-generation GM crops, because such crops have not been widely adopted. However, several authors have carried out conceptual analyses and ex ante simulations of the welfare effects under different conditions in developed countries (e.g., Jefferson-Moore & Traxler 2005, Giannakas & Yiannaka 2008).

In developing countries, the situation is different, especially when looking at technologies that are targeted to the poor, such as biofortified GM crops. Widespread production and consumption of biofortified staple crops could reduce micronutrient deficiencies, improve health outcomes, and provide economic benefits (Bouis 2007). Yet, it is uncertain if they would command higher market prices, because the poor are often not aware of their micronutrient deficiencies and may not be willing or able to pay a quality premium. Therefore, biofortified crops in developing countries may not lead to an upward shift in demand, so social welfare effects must be evaluated differently (Qaim et al. 2007).

Dawe et al. (2002) looked at the potential nutritional effects of Golden Rice by analyzing likely improvements in vitamin A intakes in the Philippines. This approach implicitly builds on a measure of program success that has been used for other micronutrient interventions, namely the achieved reduction in the number of people with micronutrient intakes below a defined threshold. However, since micronutrient intake is not an end in itself but only a means to ensure healthy body functions, it is more appropriate to go further and quantify health outcomes directly. Zimmermann & Qaim (2004) and Stein et al. (2006) suggested an alternative approach in their analyses of the potential health benefits of Golden Rice. They defined the benefit of the technology as the difference in health costs related to vitamin A deficiency with and without Golden Rice.

In their ex ante analysis, Stein et al. (2008) used representative household data from India to show that Golden Rice could reduce the health costs of vitamin A deficiency by up to 60%. They also calculated a high cost-effectiveness of Golden Rice, which compares favorably with other nutrition and health interventions, and a high social rate of return, which compares favorably with other agricultural R&D investments (Qaim et al. 2007). Anderson et al. (2005) used a macro CGE model to simulate the benefits of Golden Rice at the global level. Modeling consumer health effects among the poor as an increase in the productivity of unskilled laborers, they estimated worldwide welfare gains of over $15 billion per year, with most of the benefits accruing in Asia. In China, for instance, Golden Rice was projected to entail a 2% growth in national income (Anderson et al. 2005).

Significant economic and health benefits can also be expected for other biofortified crops, such as iron- and zinc-dense staple foods or crops containing higher amounts of essential amino acids (Qaim et al. 2007). The potentially high cost-effectiveness of biofortification in developing countries is due to the fact that the approach is self-targeting to the poor, with biofortified seeds spreading through existing formal and informal distribution channels. However, possible issues of consumer acceptance must be considered. Especially when no price premium is paid in the output market, suitable strategies to convince farmers to adopt such crops are needed. A combination of quality traits with interesting agronomic traits may be a practicable avenue.

6. CONSUMER ACCEPTANCE OF GM CROPS

In spite of the great potential of GM crops and the benefits that have already materialized, public attitudes toward the technology are often negative, and consumer acceptance remains an issue.[5] Consumer perceptions are often dominated by health, environmental,

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[5] This is in contrast to pharmaceutical applications of GM technologies, which are widely accepted by the public.

social, and ethical concerns, which are not always based on the best information but which have emerged as important driving forces of biotechnology policies (Miller & Conko 2004, Paarlberg 2008). One reason for the partial acceptance may be that most GM crops now available involve agronomic traits with limited direct benefits to consumers. Consumer acceptance may increase when second-generation, quality-enhanced GM foods or crops with combined agronomic and quality traits are introduced.

Aspects of GM crop acceptance have been widely analyzed in the literature; most studies determine consumers' WTP for GM-free foods or the willingness to accept a discount for GM foods. These findings help us understand the values consumers attach to the GM attribute especially in the absence of observable market data. There are two approaches used for estimating WTP. The first approach involves choice modeling or contingent valuation surveys to obtain stated-preference data from consumers. Most of the available studies for GM crops build on this approach, both in developed (e.g., Lusk 2003, McCluskey et al. 2003, Moon & Balasubramanian 2004) and developing countries (e.g., Kimenju & De Groote 2008, Krishna & Qaim 2008a). The advantage of stated-preference surveys is that representative data can be obtained. The disadvantage, however, is the potential hypothetical bias, as consumers state their preferences without any direct financial implications. The second approach avoids this bias through experimental auctions, although samples are usually smaller and not representative of the total population. The experiments are often designed such that participants bid with real money or are presented with opportunities to exchange a given GM product for a corresponding GM-free product or vice versa. Such experimental auctions have been used for analyzing consumer acceptance in the United States and the EU (e.g., Huffman et al. 2003, Lusk et al. 2006).

Lusk et al. (2005) provide a meta analysis, regressing the WTP results from individual studies on a set of explanatory variables. Across all studies in the analysis, the weighted mean WTP for GM-free products is a premium of 23% more than that for GM products. However, remarkable differences arise. The WTP is significantly higher in Europe than in the United States, and it is significantly lower for processed than for fresh GM foods. Studies using experimental auctions result in a lower WTP for GM-free foods on average. Individual analyses also show a significant influence of consumer characteristics such as age, education, income, or gender, but the direction of the influence is not uniform.

A difference in WTP for GM and GM-free products indicates that many consumers do not consider these options as perfect substitutes. In that case, introducing GM technology would be associated with a negative externality, which would need to be accounted for in welfare economics studies (Giannakas & Fulton 2002, Lapan & Moschini 2004). However, past experience shows that both stated-preference and experimental data do not always correctly predict actual consumer behavior. Moreover, consumer responses are strongly dependent on the type of information available at a certain point (Huffman et al. 2003), so GM acceptance may potentially change rapidly. The public media play an important role. Especially in Europe, media reports about GM crops have been predominantly negative.

In general, available studies suggest that second-generation GM foods will be more acceptable to consumers than first-generation products (Lusk et al. 2005). This supports the hypothesis that GM acceptance levels will rise when quality-enhanced crops with more direct consumer benefits become available. There are also indications that consumers in developing countries have more positive attitudes toward GM food than their counterparts in developed countries (e.g., Kimenju & De Groote 2008, Krishna & Qaim 2008a).

One possible explanation is that they are generally poorer and sometimes food insecure; thus they may be more open to productivity-increasing technologies.

7. ECONOMICS OF GM CROP REGULATION

Because GM crops are associated with several potential market failures, the technology is heavily regulated. For instance, GM crops may be associated with environmental and health externalities, so biosafety and food safety regulations have been put in place. For consumers, the GM characteristic of food products is a credence attribute, indicating that labeling regulations can help to reduce transaction costs and problems of asymmetric information. The development of GM technologies leads to public goods that can easily be reproduced, so IPR protection is needed as an incentive for private sector R&D investments. However, because every regulation is associated with trade-offs, the optimal level should be determined on the basis of solid economics research (Just et al. 2006).

7.1. Biosafety and Food Safety

Governments have an important role in ensuring that novel foods are safe for human consumption and that novel agricultural inputs do not cause major negative impacts on the environment and long-term agricultural production possibilities. Most countries, with the notable exception of the United States, consider GM crops to be novel foods, regardless of the characteristics of their final product. Hence, new laws and institutions to regulate potential biosafety and food safety issues have been established, requiring that GM products be approved before they may be grown in, consumed in, or imported into a country (Herdt 2006). Because approval processes are not internationally harmonized, they have become a major barrier to the spread of GM crops and technologies around the world. For instance, the EU has not yet approved some of the GM maize technologies that are used in the United States and Argentina, which obstructs trade not only in technologies but also in commodity and food markets. In the EU, this is related to public-acceptance problems. In other parts of the world, however, the lack of GM crop approvals is often due to human and financial capital constraints. Smaller developing countries, in particular, have been unable to legislate and operate a biosafety regulatory system to date. This has shut them off from some of the international markets (Pray et al. 2006).

In countries where a biosafety system is in place, most of regulators' efforts are put into preventing the commercialization of products that may harm people or the environment (i.e., type I errors). Often, regulators are extremely cautious, requiring many regulatory trials over a long period of time. However, lengthy biosafety and food safety testing procedures come at a cost. Kalaitzandonakes et al. (2007) estimated the private compliance costs for regulatory approval of a new Bt or HT maize technology in one country at $6–15 million. Commercializing the same technology in other countries will entail additional costs. Beyond these direct regulatory costs, there are indirect costs in terms of foregone benefits (preventing the use of safe products is referred to as type II errors). Pray et al. (2005) estimated that a two-year delay in the approval of Bt cotton in India led to aggregated losses to farmers of more than $100 million.

Such high regulatory costs slow down overall innovation rates. They also impede the commercialization of GM technologies in minor crops and small countries, as markets in such situations are not large enough to justify the fixed-cost investments. Expensive regulations are also difficult to handle by small firms and public sector organizations, thereby contributing to the further concentration of the agricultural biotech industry. Were such lengthy and complex procedures necessary to regulate high-risk products, then the costs involved would be justified. But this does not seem to be the case. Because the use of genetic engineering does not entail unique risks, it is illogical to subject GM crops to a much higher degree of scrutiny than conventionally bred crops (Bradford et al. 2005). The regulatory complexity observed today appears to be the outcome of the politicized public debate and the lobbying success of antibiotech interest groups (Miller & Conko 2004).

Some reform of the GM regulatory framework will be necessary, and economists have an important role in this respect in terms of quantifying costs and benefits. Lichtenberg & Zilberman (1988) suggested a safety rule approach for more efficient pesticide legislation under uncertainty. The same approach could also be useful in the context of GM crops. It combines a probabilistic risk assessment model with a safety rule decision mechanisms that is equivalent to the use of significance levels for statistical decision making (Sexton et al. 2007). The safety rule approach can be employed for cost-benefit or risk-benefit analyses. Hence, transparent criteria and maximization techniques are used to bring science and objectivity to decision-making processes that are often influenced by political economy considerations and a precautionary approach.

7.2. Labeling and Coexistence

Several countries have introduced or considered introducing a food-labeling system. In general, mandatory or voluntary labeling is possible. Mandatory labeling is often used to warn consumers of specific health risks (e.g., cigarettes), whereas voluntary labeling is more common to differentiate products with desirable characteristics for marketing purposes (e.g., organic). Both systems can convey the same information to consumers. Given that only GM products that are considered to be safe are approved for market release, no warning of risks is required on labels. Therefore, the issue is mainly one of heterogeneous consumer preferences, which—from an economics perspective—would be best addressed through voluntary labeling of GM-free products (Golan et al. 2001). The EU, however, has established a mandatory system, which is more costly and can reinforce the notion that GM products are inherently unsafe. The motivation underlying the EU approach is that consumers have a right to know, which is different from the need to know approach in the context of risk communication. Moschini (2008) argued that the right to know approach is too open ended and potentially unbounded, because it can be invoked for virtually anything.

Labeling involves market segregation and a system of identity preservation, which can be quite costly. The cost is negatively correlated with the threshold levels allowed for the adventitious presence of GM material. Again, these thresholds are not related to risks but are a political decision; very low thresholds can lead to prohibitive segregation costs. Giannakas & Fulton (2002) and Lence & Hayes (2005) showed that labeling in general and segregation costs in particular can influence the welfare effects of GM crops significantly. Dissimilar approaches across countries can also lead to serious problems in international trade.

Labeling and segregation are also related to coexistence. The EU, in particular, has established rules to ensure the coexistence of GM crops with conventional and GM farming, which involve a number of technical and legal specifications, from minimum distance requirements for cultivation to liability and insurance measures (Beckmann et al. 2006). The high degrees of complexity, uncertainty, and direct costs associated with these coexistence rules represent clear disincentives for EU farmers to adopt GM crops (Demont & Devos 2008, Breustedt et al. 2008).

7.3. Intellectual Property Rights and Public-Private Partnerships

In the United States and most other developed countries, living organisms and parts thereof have been patentable since the 1980s. This has spurred a tremendous amount of private sector biotechnology research. Nowadays, more than 75% of all patents in agricultural biotechnology are held by the private sector, mostly by a few large multinational corporations (Graff et al. 2003). Although strong patents and other forms of IPRs provide an incentive for private sector R&D, they are associated with higher prices and the usual static welfare losses in monopoly situations. As noted above, the degree of IPR protection in a country has an influence on GM crop adoption and benefit distribution. When GM seed prices are too high, resource-poor farmers face access problems (Qaim & de Janvry 2003). Therefore, the optimal level of IPR protection and enforcement is situation specific (Giannakas 2002).

The proliferation of IPRs on genes, processes, and technologies has led to access and freedom-to-operate problems within the biotechnology industry. Because the development of a single GM crop may require the use of dozens of patented intermediate technologies, licenses have to be negotiated with multiple parties, involving high transaction costs (Santaniello et al. 2000). In that sense, the freedom-to-operate problem may contribute to further industry concentration. Public sector research organizations, in particular, are at a disadvantage because they often have relatively little to offer in return for licenses from private companies. Even the largest public sector patent holders, such as the University of California and the United States Department of Agriculture, own less than 2% of total agricultural biotechnology patents versus the more than 10% owned by individual multinational companies such as Monsanto and DuPont (Graff et al. 2003).

However, public sector organizations combined hold 24% of the patents, and in some areas they could develop GM crops without relying on patents from the private sector. Graff & Zilberman (2001) suggested an IPR clearinghouse mechanism to reduce transaction costs for such public sector collaborations and joint ventures. A working example is the Public Intellectual Property Resource for Agriculture (PIPRA), bringing together intellectual property from more than 40 universities and public agencies and helping make their technologies available to innovators around the world (http://www.pipra.org).

Such public sector initiatives are important, as certain research and technology areas will not be addressed by private companies because of the limited size of the potential markets or other constraints. Examples include technologies designed especially for poor farmers and consumers in developing countries (Qaim et al. 2000, Lipton 2001). In such areas, more public research is needed. Moreover, more public-private partnerships should be sought to harness the comparative strengths of both sectors (Rausser et al. 2000, Byerlee & Fischer 2002). Usually, universities are better suited to carry out basic research, whereas private companies have advantages in more applied research and development

(Rajagopal et al. 2009). There are numerous examples of public-private research cooperation in agricultural biotechnology, but none of these projects has yet led to a commercialized GM crop. Ex ante studies show that well-designed partnerships can be advantageous for all parties involved (Krishna & Qaim 2007, 2008b). Nonetheless, more research is needed to develop best practices for the transfer of technologies and know-how as well as the development and commercialization of GM crops.

8. CONCLUSION

GM crops have been used commercially for more than 10 years. To date, most of the GM crops employed have been HT and insect resistant. Available impact studies show that these crops are beneficial to farmers and consumers and produce large aggregate welfare gains. Moreover, GM crops bring about environmental and health benefits. GM crops may also be well suited for small-scale farmers, because such seed technologies are scale neutral. The empirical evidence shows that Bt crops in particular can have significant income-increasing and poverty-reducing effects. Farmers in developing countries sometimes benefit more than farmers in developed countries, which is partly a result of weaker IPR protection and, thus, lower seed prices. Yet, income distribution effects also depend on the wider institutional setting, including farmers' access to suitable seed varieties, credit, information, and other input and output markets. More public and institutional support will be needed to realize the benefits for the poor on a larger scale.

GM technologies currently in the research pipeline include crops that are tolerant to abiotic stresses and crops that contain higher amounts of nutrients than traditional crops. The benefits of such applications could be much greater than the ones already observed. Against the background of a dwindling natural resource base and growing demand for agricultural products, GM crops could contribute significantly to food security and sustainable development at the global level. New technologies are crucial for the necessary production increases.

In spite of these potentials, public opinion regarding GM crops remains divided, especially in Europe. Concerns about new risks and lobbying efforts of antibiotech groups have led to complex and costly biosafety, food safety, and labeling regulations, which slow down innovation rates and lead to a bias against small countries, minor crops, small firms, and public research organizations. Overregulation has become a real threat for the further development and use of GM crops. The costs of regulation in terms of foregone benefits may be large, especially for developing countries. This is not to say that zero regulation would be desirable, but the trade-offs associated with regulation should be considered. In the public arena, the risks of GM crops seem to be overrated, while the benefits are underrated.

Economics research has an important role to play in finding ways to maximize the net social benefits. More work is needed to quantify possible indirect effects of GM crops, including socioeconomic outcomes as well as environmental and health impacts. Furthermore, economists need to contribute to the design of efficient regulations and innovation systems in light of changing framework conditions. Although the gradual move from public to private crop improvement research is a positive sign of better-functioning markets, certain institutional factors seem to contribute to increasing industry concentration. This could lead to adverse outcomes in terms of technology development and access. Such issues need further analysis.

SUMMARY POINTS

1. GM crops have been used commercially for more than 10 years in developed and developing countries. So far, herbicide-tolerant and insect-resistant Bt crops have been the primary ones employed.
2. Impact studies show that these crops are beneficial to farmers and consumers and produce large aggregate welfare gains. In many cases, farmers in developing countries benefit more than farmers in developed countries.
3. Moreover, GM crops bring about environmental and health benefits. Bt crops in particular allow significant reductions in chemical pesticides.
4. Bt crops can also be suitable for small-scale farmers. Evidence from India and other developing countries shows that they contribute to higher household incomes and poverty reduction, when embedded in a conducive institutional environment.
5. Future GM crop applications, involving tolerance to abiotic stress and higher nutrient contents, may lead to much larger benefits.
6. Against the background of a dwindling natural resource base and growing demand for agricultural products, GM crops can contribute significantly to food security and sustainable development at the global level.
7. In spite of these potentials, public opinion still regards the use of GM crops as controversial. Concerns about new risks have led to complex and costly biosafety, food safety, and labeling regulations.

FUTURE ISSUES

1. Overregulation has become a real threat for the further development and use of GM crops. The costs in terms of foregone benefits may be large, especially for developing countries.
2. Economics research has an important role to play in finding ways to maximize the net social benefits. More work is needed to quantify possible indirect effects of GM crops, including socioeconomic outcomes as well as environmental and health impacts.
3. Furthermore, economists need to contribute to designing efficient regulatory mechanisms and innovation systems.
4. Although the gradual move from public to private crop-improvement research is a positive sign of better-functioning markets, certain institutional factors seem to contribute to increasing industry concentration.
5. Especially with a view to small-scale farmers, more public research and institutional support are needed to complement private sector efforts.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

Constructive comments from David Zilberman and Steve Sexton are gratefully acknowledged. Most of my research related to the economics of GM crops was supported financially by the German Research Foundation (DFG).

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Annual Review of
Resource Economics

Volume 1, 2009

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