

Agricultural Biotechnology: Economics, Environment, Ethics, and the Future

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Abstract

Agricultural biotechnology and, specifically, the development of genetically modified (GM) crops have been controversial for several reasons, including concerns that the technology poses potential negative environmental or health effects, that the technology would lead to the (further) corporatization of agriculture, and that it is simply unethical to manipulate life in the laboratory. GM crops have been part of the agricultural landscape for more than 15 years and have now been adopted on more than 170 million hectares (ha) in both developed countries (48%) and developing countries (52%). On the basis of this substantial history and data spanning many years, the economic and environmental impacts of GM crops can now be summarized with some certainty, and the analysis indicates that, on balance, many benefits have accrued from the adoption of GM crops. There continue to be many ethical issues that are being debated, and many are being resolved through institutional interventions. The future of agricultural productivity would be better served if the genetic modification debate were less polarized and were focused on the potential for complementarity of GM technologies within a diversified farming system framework.

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1. INTRODUCTION

Agricultural technologies in their broadest sense have been responsible for supporting humankind, its population growth, and the expansion of societies' complexity for millennia. Indeed, the ability to meet the world's basic food needs while employing a smaller and smaller proportion of the human population is attributable to the development of increasingly sophisticated agricultural technologies and has

allowed the development of complex societies endowed with institutions focused on non-agricultural activities that enrich the overall quality of life. Agronomic practices involving mechanization, soil fertilization, and chemical control of pests and disease along with genetic improvement of crops have been dominant trends. Some of the greatest advances in crop productivity have involved the deliberate integration of new agronomic practices with genetic improvements. The best-known example is the Green Revolution, which integrated the increased reliance on fertilizer management with new dwarf varieties of wheat and rice. A less well-known example is the integration of mechanical harvesting with tomato varieties bred for both concentrated flowering and firm fruit (1). Both emphasize the integration of genetic and agronomic technologies to optimize crop yields and production efficiency.

There are several important applications of molecular biology and biotechnology to improve crops, including marker-assisted selection, *in vitro* propagation of plants, embryo rescue via micropropagation, and specialized mutation breeding strategies such as targeting induced local lesions in genomes (TILLING) (2). In this review, we focus on the subset of agricultural biotechnologies that involve plant genetic engineering (GE) or the transfer of foreign genes by nonsexual methods to improve crops, a technology that continues the historical trend of integrating genetic advances with agronomic practices to increase agricultural productivity. Crop GE is a technology developed in the early 1980s that reached its first commercial launch in the mid-1990s and relies on the ability to transfer novel genes to crop plants by nonsexual means. This new technology expanded the gene pool available for crop improvement from a narrow base of closely related plant species to a theoretically infinite gene pool, encompassing the genes present in all organisms as well as entirely synthetic genes. In addition to expanding the gene pool, GE, in comparison to traditional plant breeding, allows the relatively rapid and precise transfer of new traits into crop plants.

Although the first genetically modified (GM) crop was the Flavr SavrTM tomato, engineered to extend fruit shelf life and quality, the first generation of GM crops incorporates so-called production traits, which confer insect resistance, disease (virus) resistance, or herbicide tolerance. The GM crop pipeline now includes second-generation traits, which include enhanced product quality and composition, tolerance to abiotic stress, nutrient-use and photosynthetic efficiency, and nutritional enhancement, among others. **Table 1** lists 45 GM crops, in 11 different plant species, that have been commercialized worldwide to date. Notably, a few GM crops have been introduced and withdrawn from the market, potentially reflecting their lack of commercial viability, and a few GM crops have come to dominate the GM crop market and continue to increase their influence, reflecting their strong adoption by farmers globally. The most recent survey by the International Service for the Acquisition of Agri-biotech Applications shows that the total global land area of GM crops reached 170 million ha in 2012, a 100-fold increase in the adoption of biotechnology crops since 1996. Currently, a total of 59 countries have granted regulatory approval for import or use of ~30 GM crops. Of these, 28 countries, including 20 developed and 8 developing, planted commercialized GM crops in 2012 (3, 4). For the first time, planted GM cropland area in developing countries (52%) has surpassed that of developed countries (48%). Of the GM crops that have gained regulatory approval in at least one individual country (defined here as the premarket phase), ~80% contain only a first-generation trait, ~9% contain only second-generation traits, and ~11% contain both first- and second-generation traits (**Table 1**). As the research and development (R&D) pipeline advances, there is an increasing trend in the incorporation of second-generation traits as shown by genes introduced in crops during the premarket regulatory process or under field evaluation (**Figure 1**, **Table 2**, and **Supplemental Table 1**; follow the **Supplemental Material link** from the Annual Reviews home page

at <http://www.annualreviews.org>). Of the 55 GM crops in the premarket phase, roughly three-quarters contain only first-generation traits, encoding herbicide tolerance and pest resistance. About 18% (10 GM events) contain second-generation traits, and 4 GM events, representing ~7% of the pipeline, contain a combination of first- and second-generation traits. The compilation of GM crops under field trial evaluation since 2008 shows an increased emphasis on second-generation traits, representing about half of the field trials of GM crops under development (**Supplemental Table 1**). There is also an increased number of second-generation traits being evaluated in combinations, including abiotic stress tolerance, efficiency of inputs, improved nutrition, and the use of plants to produce pharmaceuticals.

The emerging innovations in the biotechnology pipeline show an increasing number of “stacked” traits, the insertion of several traits into one seed. For example, new crops may include traits that confer resistance to insects and herbicides and drought tolerance, thus combining two, three, four, or up to eight traits (e.g., Monsanto’s new corn variety SmartStax[®] has eight) (**Table 1**). Last year, 25% of the total GM cropland area consisted of crops with stacked traits grown in 13 countries, including 10 developing countries.

About 80% of the GM crops commercialized to date have been developed by the private sector (**Table 1**). Monsanto Company is the leading developer, contributing nearly 50% of the commercially available GM crops (**Table 1**). The private sector continues to dominate in the premarket phase, generating almost 90% of the innovations that reach this stage. The public sector has a much higher participation at the early stages of the R&D pipeline, conducting about 60% of the field trials (**Supplemental Table 1**). However, the public sector’s role greatly diminishes as the R&D pipeline reaches advance stages. To date, the public sector has released only ~10% of the GM crops marketed (**Table 1**).

Agricultural biotechnology and, specifically, the development of GM crops have been


 **Supplemental Material**

Table 1 Genetically modified crops commercialized worldwide as of 2013 by plant species, developer, product name, event name/gene, and traits^a

Plant species	Developer ^b	Product name	Event name/gene(s)	First-generation trait		Second-generation trait
				Pest resistance	Herbicide tolerance	Enhanced product quality, stress tolerance, altered growth
Alfalfa	Monsanto	Roundup Ready	J101/J163		•	
Carnation	Florigene	Moon series	Delphinidin-encoding gene			•
Cotton	Monsanto	Bollgard II Flex	MON88913/MON15985	•	•	
	Monsanto	Bollgard	MON531	•		
	Monsanto	Roundup Ready	MON1445		•	
	Monsanto	Bollgard II	MON15985	•		
	Monsanto	Roundup Ready Flex	MON88913		•	
	Bayer CropScience	LibertyLink	LLCotton25		•	
	Dow AgroSciences and Pioneer Hi-Bred	WideStrike	281-24-236/3006-210-23	•		
	CAAS, China	SGK321	<i>CryIA + CpTI</i>	•		
	CAAS, China	GK19	<i>CryIAb/CryIAc</i>	•		
	Nath Seeds, India	GFM	<i>CryIA</i>	•		
	JK Agri Genetics Seeds, India	JK-1	Event 1	•		
CICR, India	—	<i>CryIAc</i>	•			
Maize	Monsanto	DroughtGard	MON87460-4			• Drought tolerance
	Monsanto	Roundup Ready Corn 2	NK603		•	
	Monsanto	YieldGard Corn Borer	MON810	•		
	Monsanto	YieldGard with Roundup Ready	NK603/MON810	•	•	
	Monsanto	YieldGard rootworm	MON863	•		
	Monsanto	YieldGard VT	MON88017	•		
	Dow AgroSciences and Pioneer Hi-Bred	Herculex RW	59122	•		
	Dow AgroSciences and Pioneer Hi-Bred	Herculex I	1507	•		

(Continued)

Table 1 (Continued)

Plant species	Developer ^b	Product name	Event name/gene(s)	First-generation trait		Second-generation trait
				Pest resistance	Herbicide tolerance	Enhanced product quality, stress tolerance, altered growth
Maize (cont.)	Syngenta	Agrisure CB	Bt11	•		
	Syngenta	Agrisure GT	GA21		•	
	Syngenta	Agrisure RW	MIR604	•		
	Monsanto	VT-Double Pro	NK603/MON89034	•	•	
	Monsanto	VT-Triple	MON810/MON88017	•	•	
	Monsanto	VT-Triple Pro	MON89034/MON88017	•	•	
	Monsanto	Seminis Performance Sweet Corn	MON89034/MON88017	•	•	
	Monsanto	SmartStax	MON89034/MON88017/ DAS-59122-7/TC1507	•	•	
	CIGB, Havana	—	– (Bt toxin)	•		
	Monsanto	DroughtGard	CBI			• Drought tolerance
Papaya	Cornell Univ.	SunUp/Rainbow	55-1	•		
	China	—	—	•		
Rapeseed (canola)	Monsanto	Roundup Ready	GT73		•	
	Bayer CropScience	LibertyLink	T45		•	• Hybrid breeding system
	Bayer CropScience	InVigor	MS8 x RF3		•	• Male sterility
	Bayer CropScience	InVigor × Roundup Ready canola	EPSPS, goxv, barnase, barstar		•	• Hybrid breeding system
Soybean	Monsanto	Roundup Ready	40-3-2		•	
	Monsanto	Roundup Ready 2 Yield	MON89788		•	• Yield
Squash	Monsanto	CZW-3	Coat protein genes of CMV, ZYMV, WMV	•		
Sugar beet	KWS Germany/ Monsanto	Roundup Ready	H7-1		•	
Sweet pepper	China	—	—	•		
Tomato	China	—	—	•		
	China	—	—			• Crop handling (longer shelf life)

^aAs of March 2013, there was a total of 45 genetically modified crops, in 11 different plant species, based on a literature survey of publications and company records, which include Stein & Rodríguez-Cerezo (4), Clive (3, 127–130), Fuchs et al. (131), Monsanto (132), and Florigene Flowers (133).

^bAbbreviations: Bt, *Bacillus thuringiensis*; CAAS, Chinese Academy of Agricultural Sciences; CICR, Central Institute for Cotton Research from India; CIGB, Center for Genetic Engineering and Biotechnology in Cuba.

Supplemental Material

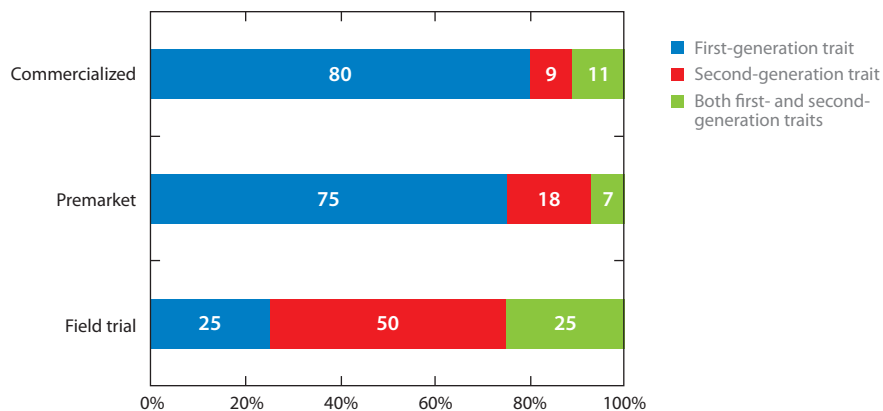


Figure 1

Distribution of first- and second-generation traits in genetically modified (GM) crops and the percentage of these in different stages of the research and development pipeline. The emerging crops under premarket and field trial phases include an increasing percentage of GM crops containing second-generation traits or both first- and second-generation traits. **Figure 1** includes data from **Tables 1** and **2** and **Supplemental Table 1**, describing GM events under the field trial evaluation, premarket, and commercialization phases.

controversial for several reasons, including concerns that the technology poses potential negative environmental or health effects, that the technology would lead to the (further) corporatization of agriculture, and that it is simply unethical to manipulate life in the laboratory. The technology underlying crop GE and the adoption of these crops have been extensively reviewed, and we refer the readers to a number of excellent resources (5, 6). The focus of this review is to examine the economic and environmental resource impacts of GM crops, the ethical issues that have been raised by this technology, and the potential impacts of GM crops that are under development for future deployment.

2. ECONOMICS OF GENETICALLY MODIFIED CROP ADOPTION AND UTILIZATION

There is a large literature on the economics of GM crops [see the surveys by Qaim (7) and Barrows et al. (8)]. Most of the economic analysis assesses the impact of pest-controlling GM crops, including two categories of traits: traits that confer insect resistance, such as *Bacillus thuringiensis* (Bt), and traits that confer resistance to herbicides, such as Roundup

Ready[®], so that the plant survives but the surrounding weeds are destroyed. Economic research on GM crops assesses the impact on cost and yields, the distributions toward various groups, environmental effects and issues of policy and regulation; these are reviewed in the following sections.

The basic framework in which to assess the benefit of pesticides is the damage control framework (9). It assumes that the output of a crop is the product of potential output and loss due to damaging pests. In addition to land, potential output depends on traditional inputs, such as fertilizer, irrigation, water, machinery, and seeds. Pest damage is a function of spatial vulnerability to pests that vary across locations and use and the efficacy of pest control strategies, including application of chemicals, adoption of integrated pest management, and GM traits. This framework has been used to develop a conceptual model that provides hypotheses about the impacts of genetic modification and when and where it will be adopted. Assuming that farmers are attempting to maximize profitability, they will utilize the technology as long as the incremental value of benefits is greater than the costs. The choice of the technology, as well as the outcome, depends on both

Table 2 Genetically modified crops in the premarket regulatory process or only authorized for commercialization in at least one country since the year 2000^a

Plant species	Developer	Event/gene ^b	First-generation traits		Second-generation trait
			Pest resistance	Herbicide tolerance	Enhanced product quality, stress tolerance, altered growth
Apple	Okanagan Specialty Fruits	Polyphenol oxidase			• Nonbrowning
Bean	Embrapa	BGMV sequences	• VR		
Beet	Monsanto	EPSPS		•	
Cotton	Aventis	Bar		•	
	Bayer	cry1Ab/cry2Ac	• IR		
	Bayer CropScience	EPSPS; 06-298-01p		•	
	Dow AgroSciences	Bta-Cry1Ac/bar	• IR	•	
	Dow AgroSciences	Bta-Cry1F/bar	• IR	•	
	Monsanto	Bt Kurstaki-Cry2Ab/B-glucuronidase	• IR		
	Monsanto	EPSPS		•	
	Syngenta	Cry1Ab	• IR		
	Syngenta	Bt-vip3A(a)	• IR		
Canola	Monsanto	EPSPS		•	
Creeping bentgrass	Monsanto	EPSPS		•	
Eucalyptus	Arborgen	CBF2/barnase			•
Maize	Dow AgroSciences	Cry34Ab1/Cry35Ab1/bar	• IR	•	
	Dow AgroSciences	Bta-Cry1F/bar	• IR	•	
	Dow	Aryloxyalkanoate dioxygenase		•	
	Genective	EPSPS		•	
	Monsanto	Glutamicum dihydrodipicolinate synthase			•
	Monsanto	Tissue-selective EPSPS		•	
	Pioneer	Amylase/DsRed2			•
	Pioneer	Vip3Aa20	• IR		•
	Pioneer	gat4621/zm-hra		•	
	Pioneer	Cry1F/Cry34Ab1/Cry35Ab1/bar	• IR	•	
	Stine Seed Farm, Inc.	EPSPS		•	
Syngenta	eCry3.1Ab/phosphomannose isomerase	• IR			

(Continued)

Table 2 (Continued)

Plant species	Developer	Event/gene ^b	First-generation traits		Second-generation trait
			Pest resistance	Herbicide tolerance	Enhanced product quality, stress tolerance, altered growth
Maize (cont.)	Syngenta	3272			•
	China	—			•
Peanut	Virginia Tech	Oxalate oxidase	• FR		
Plum	USDA-ARS	PPV sequences	• VR		
Potato	Monsanto	Bt- <i>CryIIIA</i> /EPSPS/ <i>PLRV</i> -ORF1 and 2	• IR, VR	•	
Rapeseed	Aventis	Bar		•	
	Aventis	Fertility restored/male sterile/bar		•	• Fertility restored/male sterile
	Monsanto	EPSPS/glyphosate reductase		•	
	Pioneer	Gat4621		•	
Rice	Bayer CropScience	Bar		•	
	China	Bt	• IR		
	Rockefeller Foundation	Phytoene synthase/phytoene desaturase			•
Rose	Forigene	Anthocyanin 5-acyltransferase/flavanoid 3'5'hydroxylase			
Soybean	BASF Plant Science	Acetohydroxy synthase		•	
	Bayer CropScience	4-Hydroxyphenylpyruvate dioxygenase/EPSPS		•	
	Dow AgroSciences	Aryloxyalkanoate dioxygenase/bar		•	
	Dow AgroSciences	Aryloxyalkanoate dioxygenase/bar/EPSPS		•	
	Monsanto	Bar		•	
	Monsanto	BBX32			•
	Monsanto	Dicamba monooxygenase		•	
	Monsanto	Acyl-ACP thioesterase/delta-12 desaturase/EPSPS		•	•
	Monsanto	Delta-6-desaturase/delta-15-desaturase			•
	Monsanto	<i>CryIAc</i>	• IR		
	Pioneer	Omega-6-desaturase/als		•	•
Pioneer	Gat4601/Gm-hra		•		

(Continued)

Table 2 (Continued)

Plant species	Developer	Event/gene ^b	First-generation traits		Second-generation trait
			Pest resistance	Herbicide tolerance	Enhanced product quality, stress tolerance, altered growth
Tobacco	Vector Tobacco	Quinolinate phosphoribosyltransferase antisense			•
Wheat	China	—	• FR		
	Monsanto	EPSPS		•	

^aThis study combined data from publications, business reports, and USDA records to identify 55 GE crops that are considered to be in the premarket process or authorized for commercialization in at least one country (4, 7, 134, 135). As noted, crops may contain a single or multiple first- or second-generation traits.

^bAbbreviations: BGMV, *Bean golden mosaic virus*; EPSPS, 5-enolpyruvylshikimate-3-phosphate synthase; FR, fungal resistance; IR, insect resistance; PPV, *Plum pox virus*; USDA, US Department of Agriculture; Virginia Tech, Virginia Polytechnic Institute and State University; VR, virus resistance.

agro-ecological and economic conditions. The model presented by Qaim & Zilberman (10) suggests that adoption of genetic modification is likely to increase when alternative strategies are less effective, their costs are substantial, and the cost of genetic modification licensing is relatively inexpensive. Their model suggests that the yield effect of genetic modification is likely to be higher when alternative strategies, such as pesticides, are ineffective and pest damage is high. In locations where alternative strategies are available, the introduction of genetic modification leads to a reduction in pesticide use. However, the total “yield effect” of genetic modification has several factors. First is the effect of the inserted trait, known as the “gene effect” (11). If the trait is not introduced into a locally adapted variety, but rather a generic one, there may be a yield loss because of the “germplasm effect” (12). The sum of the gene effect and germplasm effect is the “seed effect” (13). If a generic variety is GM, it may actually reduce yield in years with low pest damage owing to yield drag (a negative effect on yield that may result from inserting a specific trait that, for example, may require extra energy or may otherwise negatively affect the yield). Because pest infestation varies across time, the seed effect may vary and may be negative if the gene effect is smaller than the yield drag. In addition

to the seed effect, there is a complementarity effect resulting from changes in other inputs (such as fertilizer) in response to pest damage. When the expected seed effect is positive, the complementarity effect is likely to be positive as well, and the yield effect of genetic modification may be greater than projected by the seed effect.

There is a large literature that attempts to test this empirical model on the basis of both experimental data and field observations. The National Research Council (NRC) (14) reports a review of the literature, especially in the United States, and Smale et al. (15) and Smale (16) present a critical review on the impact of genetic modification, especially in developing countries. Smale (16) identifies differences in the quality of empirical findings. Some of the studies are often unable to control for potential biases created by sampling measurement and estimation methods. Overall, the literature [particularly the studies by Smale (16), the NRC (14), Qaim (7), and Carpenter (17)] suggests that, on average, adoption of genetic modification in cotton and maize has increased yield, reduced pest damage, reduced insecticide use, and increased farm-level profitability. However, there are incidents in which adoption results in reductions in yield per unit of land. In the case of Bt cotton, the impact in developing countries with significant pest damage tends to be higher

HT: herbicide
tolerant

than in developed countries (8). The yield effect in the case of soybean is less pronounced, but adoption of herbicide-tolerant (HT) varieties has led to expansion of agricultural land.

The quantitative impact of adoption of genetic modification varies significantly across locations and over time. The adoption literature (18–20) suggests that diffusion of new technology occurs gradually, to a large extent because of heterogeneity among potential adopters (21). Early adopters occupy locations where the adopted technology has the most advantages, but over time, adoption increases because of learning by doing (which tends to reduce the cost of the technology), learning by using, imitation, gains from scale (22), and social networks. Heterogeneity across location, variability of pest damage over time, and changes in technology and its uses contribute to the significant variability of these technological impacts. The parameters used in a recent simulation study by Bouët & Gruère (23) demonstrate differences in the impact of genetic modification in different countries. For example, on the basis of available studies, the calibrated increased yield effect of GM cotton for Argentina is 33%, pesticide reduction 46%, and labor savings 5%. For the United States, the increased yield effect is 11%, pesticide reduction 30%, and labor savings 2%. In China, the results were 7%, 67%, and 5.8%, respectively, and in South Africa, 40%, 49%, and 25%, respectively. Similar variability across countries is documented in Reference 7.

Differences in yield, pests, and labor costs across different locations determine the impact of genetic modification on profitability. When analyzing a number of studies, Qaim (7) found that economic gains per hectare (ha) for Bt cotton varied from \$23/ha in Argentina, \$58/ha in the United States, and \$91/ha in South Africa to \$135/ha in India. The gains from Bt maize also differed: \$12/ha in the United States, \$20/ha in Argentina, \$53/ha in the Philippines, and \$70/ha in Spain.

Although changes in profitability are a major driver of adoption, adoption is also affected by other factors. For example, GM technology re-

duces vulnerability to risk and can be viewed as an insurance mechanism. Crost & Shankar (24) documented the risk-reducing effect of GM crops in India. Yang et al. (25) found that risk is a dominant concern of cotton growers adopting Bt technology in China, and Liu (26) found that farmers who are more risk averse and farmers who tend to overestimate extreme risk are more likely to be early adopters. In another study, Liu & Huang (26) showed that farmers who are overly concerned with risk tend to overapply genetic modification, which may override concerns about resistance buildup (27).

Studies have found that adoption of GM crops has been affected by nonpecuniary or intangible benefits (28, 29), including increased flexibility and convenience in management, reduced exposure to toxic chemicals, and reduced effort. GM varieties do not require unique skills, yet a study by Crost et al. (30) finds that more profitable farmers in India tend to be early adopters and that less-capable farmers tend to follow later. GM varieties do not impose economies of scale. Thirtle et al. (31) suggest that Bt cotton can equally benefit smallholders in South Africa but that adoption may be constrained by credit barriers (32).

Much of the findings on the impact of GM crops were obtained through a large number of case studies that use methods ranging from simple cost budgeting to complex econometrics to assess the impact of genetic modification on particular situations. There are fewer studies on aggregate supply, which may provide a broader base for the assessment of the impact of genetic modification on supply, prices, and the welfare of both producers and consumers. Sexton & Zilberman (13) used a time-series analysis of national data on crop aggregate production, land allocation among crops, and allocation of land within crops to GM and non-GM varieties across different countries to econometrically estimate the effects of adoption of genetic modification, time, and country on average crop yields. Barrows et al. (8) expanded this study with a statistical analysis that relied on data consisting of the total output of the major crops grown using genetic

modification—cotton, maize, and soybeans—in different countries over time, as well as the total area in production and the share of the area allocated to GM technology. It decomposes yield per hectare of a crop in a given country and year into a crop effect, time effect, country effect, and GM effect on the basis of the share of genetic modification used in production in a country in a given year with a given crop.¹ The analysis was used to test whether there are differences between traditional crop yield and yield from GM crops. The analysis found that genetic modification increases yield per hectare for cotton and maize but not for soybeans. The cotton and maize estimates imply that GM seeds increase yields by 34% and 32%, respectively, relative to traditional seeds. For soybeans, the estimates imply a 2% yield improvement from GM seeds, but this was not statistically significant.²

The cotton and maize estimates are similar to those reported earlier (7), although slightly higher. The difference in relative magnitudes can be understood as a difference in population effects. The studies in Qaim (7) are primarily randomized plot-level field trials, so the yield effects can be interpreted as the average treatment effect for the GM gene. In other words, the estimates in Qaim (7) calculate the expected yield increase if a random farmer switched from traditional technology to GM technology, holding all other inputs constant. In contrast, the estimates in Barrows et al. (8) are derived from real-world outcomes, in which neither selection nor farming practices are controlled. First, because genetic modification reduces the risk of pest damage, the marginal benefit of productive inputs such as water and fertilizer increases, so their application likely increases with genetic modification adoption. The increased application of complementary inputs

likely magnifies the yield effect relative to the gene effect. Second, because genetic modification adoption is an endogenous choice at the farm level in Barrows et al.'s (8) analysis, the sample of adopters is nonrandom. There is evidence in the literature that genetic modification adopters differ from nonadopters along several dimensions that likely correlate with productivity [e.g., education (30) and risk preferences (26)]; thus, the genetic modification effect for adopters is likely different (and higher) than it would be for nonadopters. Considering both complementary inputs and selection, the estimates in Barrows et al. (8) should be interpreted as global average treatment effects on the treated, where “global” implies the overall yield effect from adopting genetic modification along with any other inputs that change with the adoption of genetic modification, and “treated” indicates that the results apply only to those that actually adopt genetic modification, not hypothetical random farmers.

The estimates in Qaim (7) and Barrows et al. (8) represent yield increases from switching to GM technology. However, the impact of genetic modification on supply comes not only from increased average yields among active farms (the intensive margin effect), but also from farmers switching to producing GM crops from either nonfarming activities or another crop (the extensive margin effect). The model in Barrows et al. (8) predicts that genetic modification technology enables the farming of poor-quality land that would be unprofitable if farmed under traditional technology. If genetic modification in fact enables such an expansion of productive land, then the total supply effect includes both the increase in production from the intensive margin yield effects and the entire production on the extensive margin. Barrows et al. (8) estimate the size of land-area expansion owing to genetic modification using year-to-year changes in both GM land area and overall land area. Cropland area broken down by traditional seed, intensive margin switching, and extensive margin recruitment is reported below. **Figure 2** plots world aggregate acreage of the three GE crops over time, decomposing

¹Pemsl et al. (27) question to what extent the gains from GM are sustainable given resistance buildup, and they suggest institutional change to slow resistance buildup and overuse of toxic chemicals with Bt crops by risk-averse farmers.

²The regression model is estimated without a constant, so the two share variables do not induce colinearity.

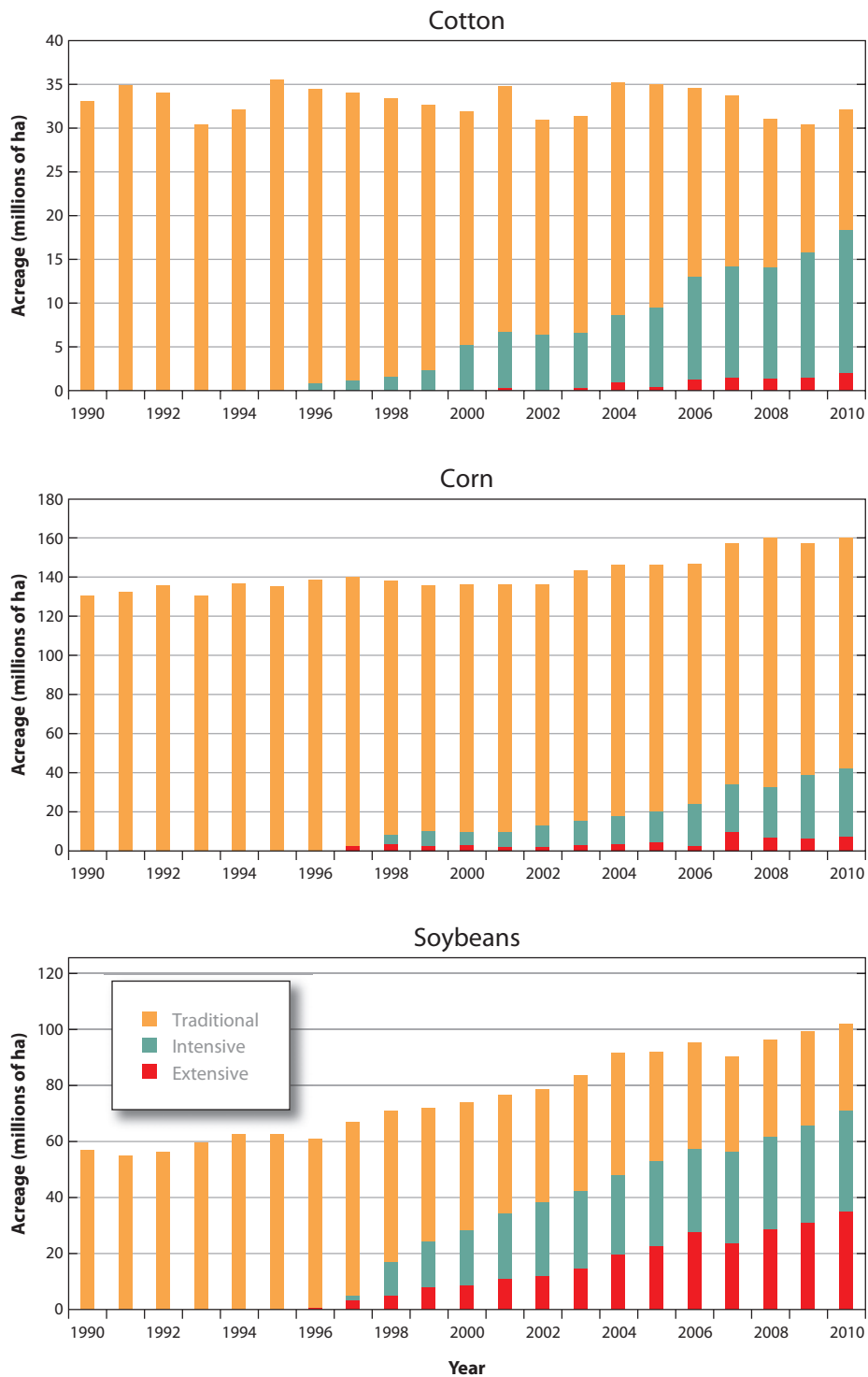


Figure 2

World acreage of the three genetically modified crops by technology and intensive/extensive margin. Abbreviation: ha, hectare.

GE acreage into land converted from traditional seed of the same crop (along the intensive margin) and land converted from other crops and nonfarming uses (along an extensive margin) (8). Barrows et al. (8) estimate that, in the case of cotton, 50% of the acreage is planted with GM seed, and out of it, 10% is in the extensive margin. The extensive margins for cotton and maize are low—on the order of 5% to 10% of total land area per crop. However, they estimate that the extensive margin for soybeans is quite large. The total world land area for soybeans has increased more than 50% since the introduction of genetic modification, and Barrows et al. (8) attribute much of this increase to extensive margin growth in Brazil and Argentina. Absent time-series plot-level data, it is difficult to say exactly where the extensive margin originates, but there is some evidence that GM soybeans allow farmers to grow in the shoulder seasons when pest pressure is usually too high. If this is the case, then the extensive margin can be interpreted as increased production on the same plot within a year, or “double cropping.” When the extensive margin effect is, to a large extent, through double cropping, the impacts of GM crops on the footprint of agriculture is minimal compared with cases in which the extensive margin implies expanding agricultural land especially by converting forestland for agricultural purposes.

In a meta-analysis, Barrows et al. (8) estimate the supply effect with and without the extensive margin. In a lower-bound case, they assume that all production on the extensive margin would have occurred even without genetic modification technology. In this case, supply effects range from 3% to 9% for maize and from 0% to 31% for cotton, depending on the yield estimate. In the upper-bound case, in which all production on the extensive margin is attributed to genetic modification, the supply effect for maize jumps to 9–19% and 18–55% for cotton. On the basis of the yield estimates in Sexton & Zilberman (13), the supply effect for soybeans ranges between 12% and 42%, depending on the share of production on the

extensive margin that one attributes to genetic modification.

Aggregate analysis allows us to assess the overall benefits of adoption and distribution of benefits among sectors. Primarily on the basis of partial equilibrium analyses for different countries, the NRC (14) presents estimates of the distribution of adoption of GM varieties and summarizes the distribution of benefits among sectors, and these results are consistent with those in Qaim (7). Their analyses suggest that early on, most (85%) of the benefits of adoption of Bt cotton and Roundup Ready soybean were shared by seed companies and farmers in the United States, but as the adoption rate increased, consumers captured half of the benefits (7). Qaim (7) reported results of general equilibrium studies assessing the global economic effect of adoption of major GM varieties. The results suggest that annual global benefits from Bt cotton were estimated to be between \$1 and \$1.8 billion between 2000 and 2005, and the annual benefit from adoption of GM maize and soybean between \$7 and \$10 billion. The predicted annual benefits from proposed GM rice varieties are estimated to be greater than \$2 billion annually. Using a general equilibrium model, Brookes & Barfoot (28) assessed the economic impacts on the farm sector of adopting GM varieties for the period 1996–2007 and concluded that the accumulative direct benefits to farmers were \$44.1 billion, equally distributed between farmers in developed and developing countries. The nonpecuniary benefits to farmers in the United States were \$5.1 billion. The benefits from GM crops were, on average, 7% of the total revenue of these crops and about 16.5% of the revenue of cotton. In another general equilibrium model, Bouët & Gruère (23) estimated the welfare effects of Bt cotton adoption by using 2008 data and found the aggregate gains to be between \$1.6 and \$3.6 billion, the gains in China between \$200 and \$260 million, and the gains in the United States between \$657 and \$881 million. The results are consistent with those from other studies (33–37).

Another concern is distributional impacts: How are the poor affected? In principle, genetic modification does not have economies of scale, so size does not matter when it comes to adoption. Indeed, for Bt cotton in India, there is 98% adoption among farmers. Subramanian & Qaim (38, 39) conducted a village study in India to simulate the direct and indirect effects of adoption of Bt cotton. The study found that the technology overall increases income by reducing labor requirements. Labor that is relieved from tasks in the field is used to earn extra income outside the farm. The relative gain from adoption of the technology is greater for poorer farmers. However, in some countries, poorer farmers may have lower adoption rates because of lack of access to credit or the supply chain, but these are not issues of the technology but are institutional (32). Bouët & Gruère (23) estimate the welfare effect of adoption of Bt cotton on the seven African nations that are in the early stages of adoption. In these countries, most production is undertaken by smallholders. They estimate that these countries will lose \$17 million annually, in aggregate, if they forgo adoption but will gain \$24 million if the rate of adoption is 50%.

3. HEALTH AND ENVIRONMENTAL IMPACTS OF GENETICALLY MODIFIED CROPS

3.1. Health Impacts

There is evidence that the adoption of GM varieties has significant health and environmental benefits (7, 14). Health benefits include reduced exposure to toxic chemicals and the resulting improved health and prevention of deaths of farmers (40). Qaim (41) provides evidence of health gains from Bt maize as well as estimates of potential gains from Golden Rice. Tan et al. (42) suggest that adoption of other GM traits in rice production in China can further improve farmworkers' health. Although there have been studies reporting negative health consequences of GM crops, they have, in general, not been corroborated, and two of the most widely pub-

licized reports of negative health consequences of GM crop consumption by rats (43, 44) were discredited on scientific grounds by the Royal Society of England (45) and the European Food Safety Authority (46). In 2008 and 2012, analyses of all available studies concluded that no adverse human health effects from GM food had been reported and/or substantiated (47, 48).

However, many GM technologies may emerge in the future, each having a unique impact on crop behavior and composition. The potential health effects of GM crops could include the introduction of new allergens not currently present in the food supply or elevated levels of toxins that naturally occur at modest levels in crops today (49). Such unexpected harmful effects have occurred thus far with traditional crop breeding, but the transfer of genes across species and from sources that are not currently present in the food supply calls for regulated pretesting and screening of new crop varieties. Such pretesting for the safety of GM crops is now commonly conducted, and there is no evidence of any allergic reactions from the consumption of current GM crop varieties. Regulatory prescreening detected and averted transfer of a gene from the Brazil nut to GM soybean because of its potential allergenicity, suggesting that the regulatory prescreening in place today is effective (49).

3.2. Greenhouse Gas Emissions

Agriculture has a significant impact on the environment, ranging from the destruction of natural habitat to accommodate extensification of agriculture to the production of 10% to 12% of the anthropogenic greenhouse gas (GHG) emissions (50). Intensification of agricultural production (higher yield from the same land area) avoids the habitat destruction associated with extensification, and a recent study concluded that the high yields associated with Green Revolution technologies avoided GHG emissions of up to 161 Gt of carbon since 1961 and that future yield improvements should be an important strategy to reduce future emissions (51). On the basis of this analysis and

the data indicating that GM crops contribute to yield enhancements of 34% (23) and above, there is a direct impact of GM technology on reducing GHG emissions resulting from the yield increases (13, 52). Note, however, that increases in yield and productivity increase profitability, which, as Angelsen & Kaimowitz (53) suggest, may lead to further expansion of production and thus a negative impact on GHG emissions. However, as we discussed above, GM crops also contribute to price reductions, and the combined impact on overall profitability of agriculture is less than that reflected by the yield effect, which will dampen the expansionary impact of the yield effect of GM crops.

In addition, the adoption of HT GM crop varieties has contributed to the adoption of low-tillage and no-tillage practices that reduce soil erosion and GHG emissions (54). In the United States, soybean land area increased by ~5 million ha between 1996 and 2009. During that same period, the area planted under no-till management increased by 65%, with the majority of growers indicating that GM HT soybean varieties had been the most significant factor in their adoption of no-till practices (55). As a result of the increased adoption of no-tillage practices enabled by GM HT varieties, average fuel consumption fell 11.8%, from 28.7 to 25.3 liters/ha, and there was an estimated decrease in GHG emissions of more than 2 Gt between 1996 and 2009. Carbon sequestration also increases under low-till and no-till management with estimates of more than 37 Gt of reduced GHG emissions between 1996 and 2009 owing to this impact of GM HT soybean varieties in the United States. Similar impacts in reducing GHG emissions are also estimated for soybean production in Argentina, Paraguay, and Uruguay, as well as for GM HT canola production in Canada (55).

GM HT maize and cotton have likely had little impact on GHG emissions because the technology has not contributed to a significant increase in low-till or no-till production systems in these crops. GM insect-resistant (IR) cotton, however, may have contributed to a decrease in GHG emissions because of the signifi-

cant reduction in the number of sprays reported relative to conventional cotton, but this impact is estimated to be relatively small (55).

3.3. Pesticide Use

In addition to the impact of agriculture on GHG emissions, the World Wildlife Fund stated that “agriculture is the leading source of pollution in many countries; in the United States alone, 428,200 metric tons of pesticides are introduced into the environment” (quoted in 56, p. 136). The major GM traits that have been commercialized to date are the first-generation traits, with a focus on improved insecticide or herbicide management (**Table 1**). Thus, it would be anticipated that these traits may replace or reduce the crops’ need for chemical pesticides (including herbicides and insecticides). In evaluating the impact of GM crops on pesticide use, the environmental impact quotient (EIQ) is often used to adjust the volumes of active ingredients used in relation to the toxicological and environmental impact of the chemical. This is a widely used indicator that is updated annually and provides a way to evaluate the environmental impact of reducing total pesticide volume as well as the impact of replacing one pesticide with another (57).

Because cotton has historically been an intensive recipient of insecticides, the most significant impact on pesticide use has been the adoption of GM IR cotton. This has resulted in the reduction of approximately 152 million kg, or 22%, of insecticide used in the United States between 1996 and 2009 with a similar impact in the developing countries that have also adopted GM IR cotton. The adoption of GM IR maize has also resulted in the reduction of approximately 36 million kg, or 40%, of insecticides used in the United States but with a much smaller impact in developing countries, presumably owing to its lower adoption rate (55). Although the estimates of insecticide reduction vary between studies (58), there does not seem to be any fundamental disagreement that GM IR crops have resulted in significant reductions in insecticide use.

IR: insect-resistant

EIQ: environmental impact quotient

The analysis of the effects of GM crops on herbicide use is less straightforward. Brookes & Barfoot (55) concluded that herbicide used on GM HT soybeans decreased by 2.2%, or 41 million kg, between 1996 and 2009 but that the overall decrease in EIQ was 16%, attributable to the shift from high-EIQ to low-EIQ herbicides. In contrast, Benbrook (58) concluded that GM HT technology contributed to a 239 million kg increase in herbicide use between 1996 and 2011, and the reasons for this discrepancy are not clear. Benbrook (58) acknowledges the generally favorable environmental and toxicological properties of glyphosate and that GM HT technology shifted herbicide use from persistent herbicides, such as imazethapyr and chlorimuron, to glyphosate but does not estimate the shift in EIQ attributable to this trend away from persistent herbicides to glyphosate. The trend of increasing herbicide use on GM HT crops relative to declining herbicide use on non-GM HT crops is attributed to the development of extremely potent herbicides that are effective at low rates for non-GM HT crops and the emergence of glyphosate-resistant weeds (see below) that require increasing rates of glyphosate application on GM HT crops.

3.4. Development of Pesticide Resistance in Insects and Weeds

The widespread use of Bt in GM IR crops and of glyphosate on GM HT crops has resulted in the development of insects resistant to Bt and of weeds resistant to glyphosate, which threaten to limit the efficacy of these GM traits. The case of Bt resistance was first observed in the diamondback moth before the introduction of GM IR crops, resulted from spraying Bt on conventional varieties (59, 60), and was consistent with models that predict the evolution of resistance within a few years of intensive selection pressure. It took almost 15 years following the release of GM IR crops, but by 2010, Bt resistance had been reported in the cereal stem borer in South Africa; the fall army worm in Puerto Rico; the pink bollworm in western

India; the cotton bollworm in the southeastern United States; the bollworm in Australia; and most recently, the Western corn rootworm in Iowa, United States, and the cotton bollworm in China (61, 62). The primary strategy to delay the evolution of Bt resistance has been to require the creation of refugia alongside GM IR crops that do not express Bt toxins and thereby allow the survival of Bt-susceptible insects. However, success of this strategy relies on a few assumptions, including the assumption that resistance mechanisms will likely be inherited as recessive traits, but there are now examples of nonrecessive or dominant resistance alleles identified in cotton bollworm (62). New and more robust strategies are needed to slow or prevent the evolution of Bt resistance. The most promising technique is the stacking of multiple Bt genes in the same plant that target the same pest. The evolution of effective resistance would require the unlikely event of two mutations that simultaneously confer resistance against both Bt proteins. In general, most new GM IR varieties released in the United States produce between two and five Bt toxins (59).

Glyphosate is the most widely used herbicide, and its widespread use has grown dramatically with the adoption of glyphosate-tolerant GM HT crops. This herbicide has been used since 1974, and by 1994, there were no reports of glyphosate-resistant weeds. However, there have now been 16 glyphosate-resistant weed species identified in 14 countries (63). The molecular basis of glyphosate resistance has been identified in several cases and appears to result from single amino acid substitutions in the active site of the enzyme (EPSP synthase) targeted by glyphosate (63) or by massive amplification of the EPSP synthase gene, as was observed in *Amaranthus palmeri* (64). The development of glyphosate-resistant *A. palmeri* is a serious agronomic problem for cotton production in the southeastern United States. In soybeans, the emergence of glyphosate-resistant horseweed has led to the use of additional herbicides and/or the more frequent application of glyphosate, which may lead to increased weed-management costs

and the reduction in environmental benefits associated with GM HR crop technology (14). The evolution of glyphosate-resistant weeds and of Bt-resistant insects requires continuous monitoring of the impacts of GM crops and investigations leading to new solutions for the deployment of GM crops. For example, Qiao et al. (65) developed and applied a framework for optimal dynamic management of Bt resistance, and Tabashnik et al. (66) proposed entirely new strategies to manage and delay Bt resistance in the cotton pink bollworm. Issues of resistance will need to be continuously addressed through use of multiple mechanisms to control pests, which may be costly.

3.5. Biodiversity

The impact of GM crops on the biodiversity of agricultural systems has multiple dimensions. First, the widespread cultivation of GM IR crops could decrease insect biodiversity by the nontarget effects of Bt, GM HT crops could decrease the availability of weeds and therefore decrease food for seed-eating birds, and the adoption of just a few GM crop varieties could result in the narrowing of genetic diversity of the crop itself.

To assess the potential for nontarget effects of Bt, early studies focused on laboratory feeding studies of Bt toxin to nontarget insects, including monarch butterflies (67), but these studies led to conclusions that were not observed in subsequent field studies (68). These feeding studies have largely been replaced with studies assessing actual nontarget risks in the field and in locales where GM crops are actually grown. For example, a reexamination of the Bt effects on monarch butterflies concluded that there was a very low probability of adverse effects of Bt maize on the nontarget butterfly (69), which agrees with a previous field study of the effects of Bt maize on black swallowtails (70). Farm-scale evaluation of Bt and non-Bt cotton in Arizona indicated that both had similar yields, largely the result of higher insecticide applications for non-Bt cotton, but the non-Bt crop also had decreased biodiversity of nontarget insects, also presumably owing to in-

creased insecticide application to the non-Bt crop (71). A meta-analysis of 42 field experiments also indicated that nontarget insects were more abundant in both Bt maize and Bt cotton fields than in those managed with conventional insecticides (72).

The concern that GM HT crops might result in a decline in bird populations gained momentum on the basis of modeling predictions that GM HT crops might threaten weed seed-eating bird populations (such as skylarks) in the United Kingdom by reducing availability of weeds for food (73). This report was followed by extensive large-scale evaluations of GM HT crops on nontarget species. However, the results of these studies were not readily generalized because they depended on the specific changes in herbicide use on individual farms (74).

Pollan (75) raised concerns about possible contributions of GM crops to reduced crop biodiversity and enhancement of monoculture agricultural practices. It is the case that most GM crops have been developed by large international companies and that small seed companies have limited or no access to GM traits, suggesting that it would be difficult to move valuable GM traits into locally adapted varieties (6). However, transgenic traits may allow the restoration of varieties that were discontinued because of pest pressure (14) and could enhance the capabilities of crops to adjust to varying conditions, thereby contributing to diversified production systems (59). Although there has been concern that GM crops might threaten biodiversity in a number of different ways, the general conclusions seem to be that agriculture itself impacts biodiversity and that GM crops do not increase this impact in a specific, predictable, or generalizable way (76).

4. ETHICS OF GENETICALLY MODIFIED CROP DEVELOPMENT, REGULATION, AND ADOPTION

GM crops have been controversial since their inception for several reasons. First, concerns

have been continuously voiced over the potential of GM crops to threaten environmental or human health, which are issues that can be addressed scientifically and through risk-benefit analysis. In addition, important drivers of this controversy have been ethical issues related to the act of modifying the DNA of living organisms; the ownership of biological innovations; and issues of equity between corporations, farmers, and the consumers. Although many of these issues would be expected to arise in the use of GE of microbes for pharmaceutical applications, they seem to be much more prominent when the application of the technology is the modification of food and especially when the benefits of the genetic modification accrue to seed companies and farmers rather than to the public. The ethical issues range from the ideological view of life itself to very practical issues of the legal frameworks for intellectual property ownership, the regulatory frameworks for assessing the risk and benefits of GM crops, and the distribution of benefits of GM crops especially in the context of food security.

4.1. Development of Genetically Modified Crops

There appears to be a fundamental philosophical division in the ethical debate about GM crops. One view is that GE of crops is an inappropriate interference with life itself. A contrasting view is that there is nothing new in our manipulation of the physical world through production of novel chemicals and of the living world through animal and plant breeding and that GM technology is simply one more step in this process (56, 77). This latter view accepts that science and technology have benefited humans in many ways and that the lessons of the past have put adequate mechanisms in place to monitor scientific innovation and to mitigate potential risks (56). The gap in this ideological division is exacerbated by the prominent role of large corporations in developing and commercializing GM crops, which introduces the additional dimensions of who is making decisions

as to how life forms are engineered and who benefits from these genetic modifications. The roles of intellectual property rights and patents and who owns crop genetic modifications are at the heart of this controversy.

4.2. Intellectual Property Rights and the Roles of the Private and Public Sectors

Most agricultural inputs (fertilizers, machinery, etc.) are provided by the private sector, but historically, the public sector provided improved crop varieties with farmers saving and reusing seeds from season to season. This made it difficult to capture the economic benefits of an investment in plant breeding. However, with the introduction of hybrid varieties and improvements in breeding technologies, it became possible to protect new crop varieties, and the share of genetic material purchased from private seed companies has increased dramatically, especially for the larger-volume crops, such as maize and soybean. Recently, there has been a growing division of labor in the generation of new crop varieties, with the public sector concentrating on generating basic knowledge or advanced germplasm and the private sector focusing on applied research, commercialization, and selling final finished varieties to farmers (14). This is particularly true for genetic modification technology, where much of the applied research is taking place in private industry, and this trend is growing, in part, as a result of stronger intellectual property rights (IPR) frameworks for plants (78). Patent rights confer monopoly power, which may be abused and require monitoring. The multinational corporations that control GM traits acquire seed companies (79), as they provide complementary assets. Thus, these companies may have strong market power in both traditionally bred and GM organisms. Shi et al. (80, 81) suggest that the resulting concentration in the market for seeds led to the pricing of seeds and product design that was more favorable to GM varieties and might have contributed to their accelerated adoption.

The availability of strong IPRs for the protection of GE methods, genes, and crop varieties has been important for the development of new GM crop varieties because they provide a period of product exclusivity, which provides innovators with the ability to recoup investments made in research and in seeking regulatory approval. The same IPRs may also result in barriers to innovation owing to the so-called tragedy of the anticommons (82), in which development of new technologies is constrained by limited access to essential or enabling patented technologies (83). This constraint on access to IP has been cited as an obstacle in developing transgenic horticultural crops (84) and as a barrier to the expansion of transgenic varieties beyond major crops (85). One outcome is that companies that control essential patented technologies are likely to invest only in the most profitable crops and traits, leaving other innovations that may have a high social value, such as meeting the needs of the poor or improving limited-market specialty crops, undeveloped (86, 87). Another by-product of the existing paradigm, whereby the public sector develops basic innovations and the private sector brings them to market, is a possible bias toward development and commercialization of product innovations, such as GM crops, rather than process innovations that include improved management practices. Both Sunding & Zilberman (88) and De Janvry & Dethier (89) suggest that there is a role for the public sector and for institutional innovation in the enhancement of adoption of process innovations and GM varieties for less-profitable markets underemphasized by the private sector.

The public research sector has contributed many of the key technologies used in GM crop development and continues to do so today, emphasizing its potential to play an important role in future developments of GM crops with high social value. To play this role effectively, the technology transfer policies of public institutions should be designed to assure that developers of technologies for crops that serve the poor or for specialty crops will have access to the enabling public-

THE PUBLIC INTELLECTUAL PROPERTY RESOURCE FOR AGRICULTURE

PIPRA (136) is an international initiative undertaken by universities, foundations, and nonprofit research institutions to make agricultural technologies more easily available for the development and distribution of subsistence crops in the developing world and specialty crops in the developed world. With the introduction of biotechnology in agriculture, researchers have a unique opportunity to contribute to the development of improved staple and specialty crop varieties. However, developing new crop varieties with biotechnology depends on access to multiple technologies, which are often patented or otherwise protected by IP rights. Ownership of these rights is fragmented across many institutions in the public and private sectors, a situation that makes it difficult to identify who holds what rights to what technologies, and in which countries. Such information is necessary, however, to establish whether or not a new crop variety is at risk of infringing those rights. The current situation thus creates barriers to commercializing new staple and specialty crop varieties. PIPRA members believed that if public-sector institutions collaborated in gathering information about and in the use of agricultural IP rights, it would be easier for them to speed up the creation and commercialization of improved staple and specialty crops and thereby fulfill part of their public mission. Specifically, PIPRA focuses on the following principal activities:

- Reviewing public-sector licensing practices
- Implementing a collective public IP asset database
- Developing shared technology packages
- Providing information, engaging other organizations, and stimulating discussions
- Engaging private-sector organizations

sector technologies even if they are patented (90, 91). Delmer et al. (92) overview some of the institutional arrangements that have emerged to reduce the IPR constraints on developers of GM crops for the poor, who are taking advantage of public-sector resources. A notable example is the Public Intellectual Property Resource for Agriculture (PIPRA; see the sidebar), an organization that provides strategies to navigate and overcome IP constraints to the development of new GM crops (93, 94).

Although IPR issues are a major concern in the development of GM crops and a topic of considerable controversy, there is recognition that strong IPRs have provided important motivation in the development of the GM varieties that have, in turn, provided both economic and environmental benefits. Also, some of the problems associated with IPRs in this sector can be addressed through improved policies and institutions. In particular, these issues require strategic balancing of the activities of the public sector to compensate for the appropriate limitations of the private sector. The interaction between the public and private sectors should take advantage of complementarities between the two, and the careful and strategic management of IPRs becomes a key ingredient in ensuring that the public and private missions of each institution are served. The private underinvestment in developing GM and other products for the poor in developing countries can be mitigated to some extent by aid agencies, the nonprofit sector, and government policies to enhance the capacity of the nascent private sector in developing countries and in technologies and breeding techniques that are complementary to genetic modification (95).

4.3. Regulation of Genetically Modified Crops

At the core of the controversy surrounding GM crops is the public concern that they may generate negative environmental and health side effects. The ethical dilemma is how to appropriately balance the risk and benefit of GM crops when different segments of the public, and indeed different nations, perceive risk quite differently. Because the largely private developers of new GM crops may not fully consider the potential impacts of GM crops, government regulatory agencies have been challenged to design policies that balance the benefits and risks of the technology (96). The regulation of GM is challenging because of the high degree of uncertainty about its impacts, and the regulatory outcomes are affected

heavily by political and economic considerations. Just et al. (97) provide an overview of the regulatory environment and an alternative analytical framework that assess these issues. Regulations are divided among biosafety, market power regulation, and food safety (which aim to reduce actual risks of GM varieties) and between labeling and coexistence (which aim to reduce exposure and use of GM varieties by individuals who want to avoid them).

Biosafety regulations have resulted in a practical ban of GM varieties in Europe and much of Africa, limiting the use of GM varieties to produce mostly fiber in Asia and feed and fiber in the Western Hemisphere. There is limited application of genetic modification in food consumed directly by humans, with papaya being a notable exception.

Regulatory research addresses several types of costs in regulating GM crops. For example, Falck-Zepeda et al. (98) demonstrated that the cost of complying with biosafety regulations in developing countries can fluctuate significantly and is a significant deterrent of adoption. Demont & Devos (99) and Demont et al. (100, 101) argue that existing coregulations in Europe that rely on rigid minimum distance rules, rather than segregation measures, allowing the freedom to negotiate among farmers, makes the introduction of GM crops very expensive. Beckmann et al. (102) investigated how differences in coexistent regulations among nations as well as heterogeneity in environmental conditions affect different patterns of adoption of GM varieties in the long run. They suggest that European countries vary in strictness of regulation, and in some countries, coexistent regulations serve as a *de facto* ban on genetic modification. Although countries such as the Czech Republic, the Netherlands, and Spain are restrictive, they allow for the adoption of GM crops, which may increase in the long run as experience accumulates. Altogether, the European regulations significantly decrease the adoption of GM crops in Europe.

The impact of adoption can provide a foundation to estimate the loss from banning the

adoption of genetic modification technologies in other countries with similar political and economic conditions. Sexton & Zilberman (13) suggest that the ban on the adoption of GM maize and soybean in Europe and Africa increases the prices of these crops by approximately the same amount as the diversion of grain to biofuel production. These results are consistent with the computable general equilibrium estimates of Anderson & Jackson (103), who found substantial welfare gains from adoption of GM coarse grains, and estimates that these gains will double if the nonadopters of GM coarse grains in Asia, Africa, and Europe adopt GM maize. They estimate that if Africa allows adoption of GM varieties in coarse grains, the gain will be substantial, and much bigger than potential losses due to reduced access to European markets. Anderson et al. (104) derive the welfare losses associated with lower costs of production, lower prices, and health benefits from banning adoption of GM rice, coarse grains, and oilseeds in Asian countries.

One of the major costs of regulation is a resulting reduction in innovative activities. Graff et al. (105) identify a wide array of product-quality and other innovations in the R&D pipeline, and they detect a significant contraction in the rate of discovery and development around 1998, which is associated with changes in the regulatory environment, especially in Europe. Potrykus (106) uses the case of Golden Rice to illustrate that the high cost of money and time associated with regulation makes innovation very expensive and reduces the range of GM products that can be developed. Kalaitzandonakes et al. (107) also suggest that high compliance costs factor into the low rate of new biotechnology innovation and that the regulatory costs tend to increase over time, arguing that there is the potential to drastically reduce these costs by eliminating redundancies to enhance the rate of return of investment on agricultural biotechnology developments.

There is a large body of literature aiming to explain differences in regulation of GM crops among nations. Regulatory decisions are a re-

sult of political systems and are viewed as results of the outcome of interactions between groups with varying political power and credibility within political and economic systems (86). In the case of GM crops (108), the clear supporters of GM crop adoption are firms and researchers that develop the technology, but firms that produce alternative products, such as pesticides, may oppose it. Retailers may be quite neutral to the technology and refuse to carry it if it disrupts business, and environmental groups tend to oppose GM crop adoption for various reasons (109).

Consumers' attitude toward the various technologies is very important, as they are buyers and voters. Consumers can be segmented into groups of varying attitudes toward genetic modification technology (110), which are reflected in their willingness to pay (or not to pay) for genetic modification-free foods or for labeling of genetic modification (111, 112). Colson & Huffman (113) argue that some groups are willing to pay extra for GM products with extra nutritional value, and their choices are affected by information availability and framing (114, 115). Both opponents and proponents of genetic modification technology aim to change consumer attitude toward the technology, which is affected by consumers' trust in these respective groups as well as in government, and, in particular, in its ability to regulate the technology (116).

Differences in regulation among countries may reflect differences in the power of interest groups, perceptions of the technology and its implementation, and the country's specific political situation. The United States was more positively disposed toward GM crops than Europe because of the dominance of Monsanto and other American agribusiness firms in the industry and because of the importance of the pesticide sector, which was likely to lose out to the technology in Europe (108). Furthermore, lack of trust in governments' ability to regulate the technology affected public attitude toward GM crops in Europe (117). Gaskell et al. (118) also argue that consumers' negative attitude toward

genetic modification technology in Europe was, to a large extent, affected by perception of the risk of GM crops and a lack of awareness of its benefits. Thus, assessment and communication of the benefits of GM crops are very important in the policy debate over their regulation (119).

Pollack & Shaffer (120) argue that current international differences in GM crop regulations have been affected by the evolution of regulation of GM crops in the United States and Europe. Paarlberg (121) argues that attitudes toward GM crops in the developing world depend on the relative influences of the United States versus Europe. Although Latin American nations are more positively disposed to adopt GM crops, African countries, with the exception of South Africa, are more economically dependent on and socially linked to Europe, which affects their negative attitudes and has effectively kept GM crop technology out of the countries where its impact could be the greatest.

5. THE FUTURE OF GENETICALLY MODIFIED CROP DEVELOPMENT

GM crops are anticipated by many to play a significant role in the arsenal of technologies that will be required to support global food security and agricultural sustainability in the next 35 years as the population moves toward its steady state of 9 to 11 billion people (59). Given the long time frames required to move an idea or new genetic technology from the laboratory to full-scale production, it is instructive to consider what new GM crops are in the pipeline today and to speculate as to what traits may be important to support food security under the predicted climate change scenarios. When examining new GM crops in the advanced R&D pipeline (crops with approved field trial records) or in the premarket regulatory process (with commercial authorization in one or a few countries), the first-generation traits continue to prevail (**Table 2** and **Supplemental Table 1**). However, second-generation crops with enhanced product quality (i.e., enhanced oil or modified composition), climate change traits (tolerance to abiotic stress-drought tol-

erance), and nutritional enhancement (vitamin and mineral) are emerging.

The emerging R&D pipeline includes GM crops that have never been deregulated before, such as vegetables, fruits, and crops important for food security (chickpea, cassava, banana, etc.). The remaining question is whether these crops will enter the market. Graff et al. (105) analyzed the agricultural innovation pipeline from the 1990s into the 2000s and noticed a steady increase of innovations from 20 innovations per year in the early 1990s to about 120 innovations at the end of the decade. However, by the late 1990s, innovation reached a plateau and started dipping in 2000. Market entrance of specialty or food security crops is questionable because, in spite of the obvious benefits and confirmation of safety by international scientific organizations, the lack of science-based and cost- and time-effective regulatory systems continues to be a major hurdle that halts the R&D pipeline (122, 123). The lack of profit potential in smaller markets or in crops for developing countries puts additional pressure on the public sector and not-for-profit organizations to identify funding opportunities and mechanisms to develop GM crops for social responsibility.

Lobell et al. (124) prioritized climate change adaptation needs for food security by identifying 12 major food-insecure regions and ranking the likelihood of having a negative impact of climate change on agricultural productivity by 2030. South Asia wheat, Southeast Asia rice, and southern Africa maize were ranked as the most important crops/regions that would likely benefit from adaptation research investments. Although this study did not address the potential role of GM crops, one can infer that this might be part of a research investment portfolio to address climate change and food security in these regions. It is also obvious to expect that traits such as drought tolerance, high-temperature tolerance, and adaptation to high CO₂ levels may all be beneficial in a future characterized by global climate change. Increasing the efficiency of water use in crops through GE has been an important focus of the private and public sector. The first GM

crop with drought tolerance, DroughtGard™ maize, will be commercially released in the United States in 2013 and is anticipated to be released in sub-Saharan Africa by 2017.

Another promising, yet challenging, application of GE is in forestry species that play an important role in carbon sequestration and preservation of biodiversity and natural ecosystems. Tree farming continues to be important for wood products, yet production is continuously threatened by biotic and abiotic stresses. Lidder & Sonnino (125) report field trials for four tree genera: *Populus*, *Pinus*, *Liquidambar*, and *Eucalyptus*, with agronomic traits for insect resistance, herbicide tolerance, and yield increase. Thus far, China remains the only country to commercialize GM poplar trees, which are grown on ~300 to 500 ha (125).

The rate of adoption of GM crops thus far shows that this technology is the fastest-adopted crop technology in modern agricultural history. The documented production and the environmental and consumer benefits, discussed in this review, explain why when given the choice farmers adopt GM crops in both developed and developing countries. It remains to be seen whether the onerous regulatory structure, trade, acceptance, investment, and intellectual property issues will allow the emerging pipeline to reach the market.

6. CONCLUSIONS

GM crops have become a major tool for pest control; they include three major crops (maize, cotton, and soybean) with two major traits (insect resistance and herbicide tolerance). These major GM crops have increased the supply of these commodities substantially and have reduced the price of feed and, indirectly, the price of food, thus providing a significant economic benefit to millions of consumers. GM crops have also reduced the agriculturally related GHG emissions, reduced erosion, and substantially decreased the use of the most toxic agricultural chemicals. Concerns that GM crops might reduce biodiversity in a variety of ways remain unsubstantiated, but there is clear

evidence that insect resistance to Bt and weed resistance to glyphosate have developed as a result of the widespread adoption of GM crops. This represents a challenge for the technology to overcome, and clear strategies are being developed to manage and delay resistance development.

The controversy surrounding the development, deployment, and adoption of GM crops has multiple dimensions. One dimension is simply an objection to manipulation of life, and another is the recognition of GE as a simple extension of tradition technologies of plant breeding. Other ethical dimensions include the increased role of large corporations in agricultural research and in the ownership of intellectual property, which can supersede traditional practices of seed saving and may constrain innovation leading to the underdevelopment of varieties to meet the needs of specialty crops as well as the poor in developing countries. Although genetic modification technology is often portrayed as a monolithic player in the agricultural landscape, there is potential for complementarity between precision farming, organic farming, and transgenic technologies within a diversified farming system framework, and this type of integrated approach should be a goal of future research.

Concerns about the environmental and human health risks of GM crops have perhaps occupied the greatest debate, and these have driven the development of regulatory frameworks to evaluate each GM crop. This essential framework is not harmonized globally, and its excessive cost is slowing the development and introduction of new technologies, in many cases, in parts of the world that would benefit most from the technology. The potential impact of GM crops is great, and indeed, these crops are likely to make critical contributions to food security and adaptation to climate change, but these potential benefits will be hampered, delayed, and diminished in the absence of major reform and harmonization of the frameworks regulating GM crops (106).

Genetic modification technologies are in their infancy and are coevolving with

accumulating knowledge, institutions, and policy regimes. The continuous evolution of genetic modification technologies should be an area of future research. Some of the lines of research reviewed here must continue, and further understanding of the impact of various genetic modification technologies on agricultural productivity, commodity prices, land-use changes, farm structure, and the environment is needed. The impacts of intellectual property and monopoly power on the evolution of the technology and its utilization are important for future work to better assess regulatory regimes and public policy. The political economy of GM crops and their impact on regulatory frameworks also deserve further attention. New evidence about the performance of the technology and technological change should be incorporated in the continuous adaptation of regulation of the technology. Genetic modification

technology is only part of an important wave of new approaches to agricultural production within the context of sustainability, and more efforts should be directed to understanding the role of genetic modification in a larger technological and societal context. The research priorities identified in the area of agroecology are also relevant for the evolving research on GM crops, and the integration of GM crops into agricultural systems should be considered as well (126). Finally, the future of GM crops and their effective integration into agricultural production systems in both developed and developing economies will depend on transparent and effective communication strategies that inform public awareness and the understanding of the role of technology (including biotechnology) in agricultural production in general and of genetic modification technology in particular.

SUMMARY POINTS

1. GM crops have been rapidly adopted. By 2012, GM crops were grown on more than 170 million ha, and for the first time, more than half of this land was located in developing countries.
2. The economic benefits of GM crops can now be fully described and apportioned according to the prevailing national economic and agronomic conditions. For example, the calibrated yield effect of GM cotton for Argentina is 33%, pesticide reduction 46%, and labor savings 5%, whereas for the United States, the yield effect is 11%, pesticide reduction 30%, and labor savings 2%. The cumulative direct benefits to farmers between 1997 and 2007 are estimated to be \$44.1 billion, equally distributed between farmers in developed and developing countries.
3. GM crops contribute to reduced GHG emissions by increasing yields and by allowing the expansion of no-till or low-till agronomic practices. GM crops, especially GM IR cotton, have contributed to a large reduction in insecticide use globally, whereas there are contradictory estimates of the effect of GM HT crops on herbicide use. In spite of early concerns, there is no evidence supporting a specific role of GM crops in reducing the biodiversity of nontarget organisms in agricultural settings.
4. There is evidence of the emergence of Bt-resistant insects and glyphosate-resistant weeds resulting from the widespread use of GM IR and GM HT crops. Issues of resistance need to be continuously addressed through the use of multiple mechanisms to control pests, which may be costly.

5. Ethical issues related to GM crops include personal beliefs about science and the ability of humans to manipulate life in new ways, the role of intellectual property and who owns new GM crops and their components, and the regulatory frameworks that assess the risks of GM crops and ultimately govern who will benefit from the new technology. Some of these issues may be resolved through new institutional interventions, but others will remain controversial.
6. There is a robust pipeline of new GM crops that addresses both agronomic traits and so-called second-generation traits conferring improved nutritional quality or other industrial output traits. Importantly, some of these new crops address anticipated climate change impacts to agriculture and may be one strategy for adaptation. The movement of these new GM crops toward commercialization depends on the intrinsic value of the new trait and on the evolution of the regulatory environment for GM crops.

FUTURE ISSUES

1. The almost exclusive role of large corporations in the development of GM crops has created intellectual property barriers for a broader participation in the development of GM crops, leaving specialty crops and subsistence crops largely out of the technological advances. The emergence of public-private partnerships is a promising development for a much broader expansion of the benefits of genetic modification technology.
2. The polarized debate over the development and adoption of GM crops has framed them as monolithic players in the agricultural landscape. Instead, there is the potential for complementarity between precision farming, organic farming, and transgenic technologies within a diversified farming system framework, and this type of integrated approach should be a goal of future research.
3. The regulatory framework for GM crops needs to be overhauled with an effort toward science-based risk and benefit assessment and global harmonization.
4. The potential for adverse health effects of GM crops poses particular challenges for a scientific review because the published literature (much of which is not peer reviewed) is such a mess, replete with anecdotal and/or sensationalized reports that have been uniformly discredited. It is hard to review reports that have been so strongly discredited in a scientific review; instead, we rely on the published meta-analyses (47, 48). For those seeking a credible review of the issues and concerns arising from this vast popular literature, we suggest Jaffe (49). However, it is certain that this topic will continue to be of great public interest, and the credible research and assessment of these concerns deserve greater and more systematic scientific attention than they have received to date.
5. There are emerging issues related to the genetic modification of livestock and fish. A review at this point would rely on models or projections of future impacts and issues and so would inevitably be speculative. A similar review of GM crops before they were actually commercialized would probably not have correctly projected the range of environmental and consumer acceptance issues that have materialized. In the first place, the regulatory challenge is to appropriately screen these innovations regarding food safety, public health, and environmental and social impacts. Subsequently, the scientific challenge will be to critically and credibly assess the balance of risks, benefits, and costs.

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