CHAPTER 1

Plant Agriculture: The Impact of Biotechnology

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1.0. CHAPTER SUMMARY AND OBJECTIVES

1.0.1. Summary

Since the first stably transgenic plant produced in the early 1980s and the first commercialized transgenic plant in 1995, biotechnology has revolutionized plant agriculture. More than a billion acres of transgenic cropland has been planted worldwide, with over 50 trillion transgenic plants grown in the United States alone. In the United States, over half of the corn and cotton and three-quarters of soybean produced are transgenic for insect resistance, herbicide resistance, or both. Biotechnology has been the most rapidly adopted technology in the history of agriculture and continues to expand in much of the developed and developing world.

1.0.2. Discussion Questions

1. What biotechnology crops are grown and where?
2. Why do farmers use biotech crops?
3. How has the adoption of plant biotechnology impacted on the environment?

1.1. INTRODUCTION

The year 2005 saw the tenth commercial planting season of genetically modified (GM) crops, which were first widely grown in 1996. In 2006, the billionth acre of GM crops was planted somewhere on Earth. These milestones provide an opportunity to critically assess the impact of this technology on global agriculture. This chapter therefore examines

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specific global socioeconomic impacts on farm income and environmental impacts with respect to pesticide usage and greenhouse gas (GHG) emissions of the technology.[1]

1.2. BIOTECHNOLOGY CROPS PLANTINGS

Although the first commercial GM crops were planted in 1994 (tomato), 1996 was the first year in which a significant area [1.66 million hectares (ha)] of crops were planted containing GM traits. Since then there has been a dramatic increase in plantings, and by 2005/06, the global planted area reached approximately 87.2 million ha.

Almost all of the global GM crop area derives from soybean, maize (corn), cotton, and canola (Fig. 1.1).[2] In 2005, GM soybean accounted for the largest share (62%) of total GM crop cultivation, followed by maize (22%), cotton (11%), and canola (5%). In terms of the share of total global plantings to these four crops accounted for by GM crops, GM traits accounted for a majority of soybean grown (59%) in 2005 (i.e., non-GM soybean accounted for 41% of global soybean acreage in 2005). For the other three main crops, the GM shares in 2005 of total crop production were 13% for maize, 27% for cotton, and 18% for canola (i.e., the majority of global plantings of these three crops continued to be non-GM in 2005). The trend in plantings of GM crops (by crop) from 1996 to 2005 is shown in Figure 1.2. In terms of the type of biotechnology trait planted, Figure 1.3 shows that GM

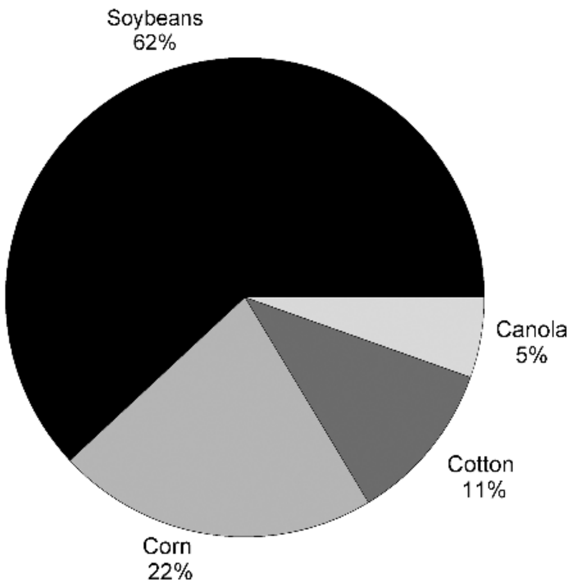

Figure 1.1. Global GM crop plantings in 2005 by crop (base area: 87.2 million ha). (*Sources*: ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio.)

[1]Brookes G, Barfoot P (2007): Gm crops: The first ten years—global socio-economic and environmental impacts. *AgbioForum* **9**:1–13.

[2]In 2005 there were also additional GM crop plantings of papaya (530 ha) and squash (2400 hectares) in the United States.

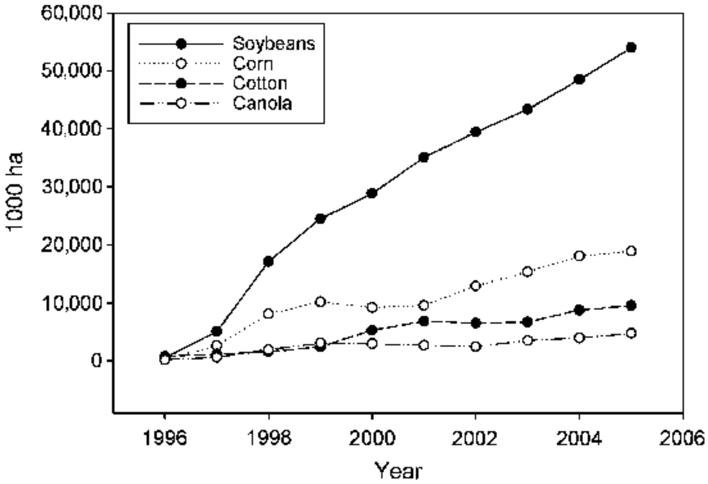

Figure 1.2. Global GM crop plantings by crop 1996–2005. (*Sources*: ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio.)

herbicide-tolerant soybean dominate, accounting for 58% of the total, followed by insect-resistant (largely Bt) maize and cotton with respective shares of 16% and 8%.[3] In total, herbicide tolerant crops (GM HT) account for 76%, and insect resistant crops (GM IR) account for 24% of global plantings. Finally, looking at where biotech crops have been grown, the United States had the largest share of global GM crop plantings in 2005

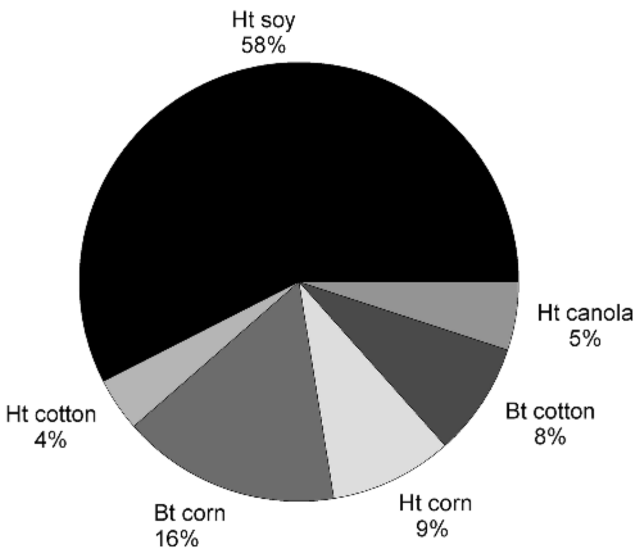

Figure 1.3. Global GM crop plantings by main trait and crop: 2005. (*Sources*: Various, including ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio.)

[3]The reader should note that the total number of plantings by trait produces a higher global planted area (93.9 million ha) than the global area by crop (87.2 million ha) because of the planting of some crops containing the stacked traits of herbicide tolerance and insect resistance (e.g., a single plant with two biotech traits).

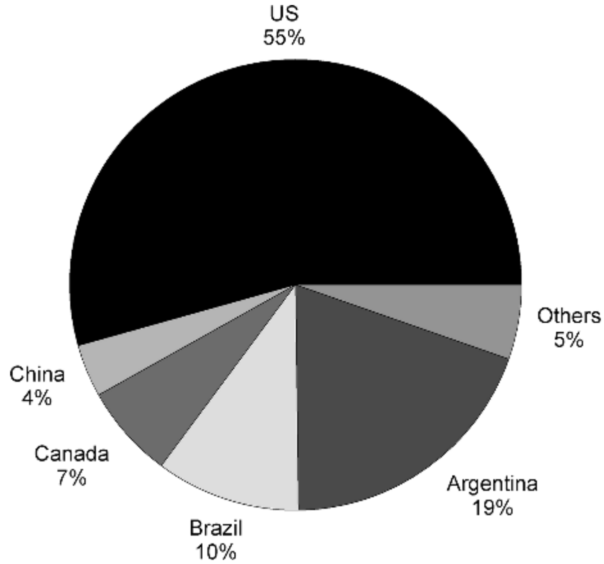

Figure 1.4. Global GM crop plantings 2005 by country. (*Sources*: ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio.)

(55%: 47.4 million ha), followed by Argentina (16.93 million ha: 19% of the global total). The other main countries planting GM crops in 2005 were Canada, Brazil, and China (Fig. 1.4).

1.3. WHY FARMERS USE BIOTECH CROPS

The primary driver of adoption among farmers (both large commercial and small-scale subsistence) has been the positive impact on farm income. The adoption of biotechnology has had a very positive impact on farm income derived mainly from a combination of enhanced productivity and efficiency gains (Table 1.1). In 2005, the direct global farm income benefit from GM crops was $5 billion. If the additional income stemming from second crop soybeans in Argentina is considered,[4] this income gain rises to $5.6 billion. This is equivalent to having added between 3.6% and 4.0% to the value of global production of the four main crops of soybean, maize, canola, and cotton, a substantial impact. Since 1996, worldwide farm incomes have increased by $24.2 billion or $27 billion inclusive of second-crop soybean gains in Argentina directly because of the adoption of GM crop technology.

The largest gains in farm income have arisen in the soybean sector, largely from cost savings, where the $2.84 billion additional income generated by GM HT soybean in 2005 has been equivalent to adding 7.1% to the value of the crop in the GM-growing countries, or adding the equivalent of 6.05% to the $47 billion value of the global soybean crop in 2005. These economic benefits should, however, be placed within the context of a significant increase in the level of soybean production in the main

[4]The adoption of herbicide-tolerant soybean has facilitated the adoption of no and reduced tillage production practices, which effectively shorten the production season from planting to harvest. As a result, it has enabled many farmers in Argentina to plant a crop of soybean immediately after a wheat crop in the same season (hence the term *second-crop soybean*). In 2005, about 15% of the total soybean crop in Argentina was second-crop.

TABLE 1.1. Global Farm Income Benefits from Growing GM Crops 1996–2005 (million US $)

Trait and Crop	Increase in Farm Income, 2005	Increase in Farm Income, 1996–2005	Farm Income Benefit in 2005 as % of Total Value of Production of These Crops in GM-Adopting Countries	Farm Income Benefit in 2005 as % of Total Value of Global Production of These Crops
GM herbicide-tolerant soybean	2281 (2842)	11,686 (14,417)	5.72 (7.1)	4.86 (6.05)
GM herbicide-tolerant maize	212	795	0.82	0.39
GM herbicide-tolerant cotton	166	927	1.16	0.64
GM herbicide-tolerant canola	195	893	9.45	1.86
GM insect-resistant maize	416	2,367	1.57	0.77
GM insect-resistant cotton	1,732	7,510	12.1	6.68
Others	25	66	N/A	N/A
Totals	5027 (5588)	24,244 (26,975)	6.0 (6.7)	3.6 (4.0)

Notes: Others = virus-resistant papaya and squash, rootworm resistant maize. Figures in parentheses include second-crop benefits in Argentina. Totals for the value shares exclude "other crops" (i.e., relate to the four main crops of soybeans, maize, canola and cotton). Farm income calculations are net farm income changes after inclusion of impacts on costs of production (e.g., payment of seed premia, impact on crop protection expenditure). (N/A = not applicable.)

GM-adopting countries. Since 1996, the soybean area and production in the leading soybean producing countries of the United States, Brazil, and Argentina increased by 58% and 65%, respectively.

Substantial gains have also arisen in the cotton sector through a combination of higher yields and lower costs. In 2005, cotton farm income levels in the GM-adopting countries increased by $1.9 billion and since 1996, the sector has benefited from an additional $8.44 billion. The 2005 income gains are equivalent to adding 13.3% to the value of the cotton crop in these countries, or 7.3% to the $26 billion value of total global cotton production. This is a substantial increase in value-added terms for two new cotton seed technologies.

Significant increases to farm incomes have also resulted in the maize and canola sectors. The combination of GM IR and GM HT technology in maize has boosted farm incomes by over $3.1 billion since 1996. An additional $893 million has been generated in the North American canola sector.

Overall, the economic gains derived from planting GM crops have been of two main types: (1) increased yields (associated mostly with GM insect-resistant technology) and (2) reduced costs of production derived from less expenditure on crop protection (insecticides and herbicides) products and fuel.

Table 1.2 summarizes farm income impacts in key GM-adopting countries highlighting the important direct farm income benefit arising from growing GM HT soybeans in

TABLE 1.2. GM Crop Farm Income Benefits during 1996–2005 in Selected Countries (million US $)

Country	GM HT Soybean	GM HT Maize	GM HT Cotton	GM HT Canola	GM IR Maize	GM IR Cotton	Total
USA	7570	771	919	101	1957	1627	12,945
Argentina	5197	0.2	4.0	N/A	159	29	5389.2
Brazil	1367	N/A	N/A	N/A	N/A	N/A	1367
Paraguay	132	N/A	N/A	N/A	N/A	N/A	132
Canada	69	24	N/A	792	145	N/A	1031
South Africa	2.2	0.3	0.2	N/A	59	14	75.7
China	N/A	N/A	N/A	N/A	N/A	5168	5168
India	N/A	N/A	N/A	N/A	N/A	463	463
Australia	N/A	N/A	4.1	N/A	N/A	150	154.1
Mexico	N/A	N/A	N/A	N/A	N/A	55	55
Philippines	N/A	N/A	N/A	N/A	8	N/A	8
Spain	N/A	N/A	N/A	N/A	28	N/A	28

Note: Argentine GM HT soybeans includes second crop soybeans benefits.

Argentina, GM IR cotton in China, and a range of GM cultivars in the United States. It also illustrates the growing level of farm income benefits obtained in developing countries such as South Africa, Paraguay, India, the Philippines, and Mexico from planting GM crops.

In terms of the division of the economic benefits, it is interesting to note that farmers in developing countries derived the majority of the farm income benefits in 2005 (55%) relative to farmers in developed countries (Table 1.3). The vast majority of these income gains for developing country farmers have been from GM IR cotton and GM HT soybean.[5]

Examination of the cost farmers pay for accessing GM technology relative to the total gains derived shows (Table 1.4) that across the four main GM crops, the total cost was equal to about 26% of the total farm income gains. For farmers in developing countries the total cost is equal to about 13% of total farm income gains, while for farmers in

TABLE 1.3. GM Crop Farm Income Benefits, 2005: Developing Versus Developed Countries (million US $)

Crop	Developed	Developing[a]	% Developed	% Developing
GM HT soybean	1183	1658	41.6	58.4
GM IR maize	364	53	86.5	13.5
GM HT maize	212	0.3	99.9	0.1
GM IR cotton	354	1378	20.4	79.6
GM HT cotton	163	3	98.4	1.6
GM HT canola	195	0	100	0
GM VR papaya and squash	25	0	100	0
Totals	2496	3092	45	55

[a]Developing countries include all countries in South America.

[5]The author acknowledges that the classification of different countries into "developing" or "developed country" status affects the distribution of benefits between these two categories of country. The definition used here is consistent with the definition used by others, including the International Service for the Acquisition of Agri-Biotech Applications (ISAAA) [see the review by James C (2006) Global Status of GM Crops 2006 ISAAA Brief No 35.].

TABLE 1.4. Cost of Accessing GM Technology[a] (in % Terms) Relative to Total Farm Income Benefits, 2005

Crop	All Farmers	Developed Countries	Developing Countries
GM HT soybean	21	32	10
GM IR maize	44	43	48
GM HT maize	38	38	81
GM IR cotton	21	41	13
GM HT cotton	44	43	65
GM HT canola	47	47	N/A
Totals	26	38	13

[a]Cost of accessing the technology is based on the seed premia paid by farmers for using GM technology relative to its conventional equivalent.

developed countries the cost is about 38% of the total farm income gain. Although circumstances vary among countries, the higher share of total gains derived by farmers in developing countries relative to farmers in developed countries reflects factors such as weaker provision and enforcement of intellectual property rights.

In addition to the tangible and quantifiable impacts on farm profitability presented above, there are other important, more intangible (difficult to quantify) impacts of an economic nature. Many studies on the impact of GM crops have identified the factors listed below as being important influences for adoption of the technology.

1.3.1. Herbicide-Tolerant Crops

- This method provides increased management flexibility due to a combination of the ease of use associated with broad-spectrum, postemergent herbicides like glyphosate (often referred to by its more commonly known brand name of Roundup) and the increased/longer time window for spraying.
- In a conventional crop, postemergent weed control relies on herbicide applications before the weeds and crop are well established. As a result, the crop may suffer "knockback" to its growth from the effects of the herbicide. In the GM HT crop, this problem is avoided because the crop is tolerant to the herbicide and spraying can occur at a later stage when the crop is better able to withstand any possible knockback effects.
- This method facilitates the adoption of conservation or no-tillage systems. This provides for additional cost savings such as reduced labor and fuel costs associated with plowing.
- Improved weed control has contributed to reduced harvesting costs—cleaner crops have resulted in reduced times for harvesting. It has also improved harvest quality and led to higher levels of quality price bonuses in some regions (e.g., Romania).
- Potential damage caused by soil-incorporated residual herbicides in follow-on crops has been eliminated.

1.3.2. Insect-Resistant Crops

- For production risk management/insurance purposes, this method eliminates the risk of significant pest damage.
- A "convenience" benefit is derived because less time is spent walking through the crop fields to survey insects and insect damage and/or apply insecticides.

- Savings in energy use are realized—associated mainly with less frequent aerial spraying.
- There are savings in machinery use (for spraying and possibly reduced harvesting times).
- The quality of Bt maize is perceived as superior to that of non-Bt maize because the level of fungal (*Fusarium*) damage, which leads to mycotoxin presence in plant tissues, is lower with Bt maize. As such, there is an increasing body of evidence that *Fusarium* infection levels and mycotoxin levels in GM insect resistant maize are significantly (5–10-fold) lower than those found in conventional (nonbiotech) crops. This lower mycotoxin contamination in turn leads to a safer food or feed product for consumption.
- There Health and safety for farmers and farmworkers is improved (handling and use of pesticides is reduced).
- The growing season is shorter (e.g., for some cotton growers in India), which allows some farmers to plant a second crop in the same season (notably maize in India). Also some Indian cotton growers have reported commensurate benefits for beekeepers as fewer bees are now lost to insecticide spraying.

1.3.3. Conclusion

It is important to recognize that these largely intangible benefits are considered by many farmers as the primary reasons for adoption of GM technology, and in some cases farmers have been willing to adopt for these reasons alone, even when the measurable impacts on yield and direct costs of production suggest marginal or no direct economic gain. As such, the estimates of the farm level benefits presented above probably understate the real value of the technology to farmers. For example, the easier and more convenient weed control methods and facilitation of no/reduced tillage practices were cited as the most important reason for using GM herbicide-tolerant soybean by US farmers when surveyed by the American Soybean Association in 2001.

With respect to the nature and size of GM technology adopters, there is clear evidence that farm size has not been a factor affecting use of the technology. Both large and small farmers have adopted GM crops. Size of operation has not been a barrier to adoption. In 2005, 8.5 million farmers, more than 90% of whom were resource-poor farmers in developing countries, were using the technology globally. This is logical. The benefit is in the seed, which must be planted by both small and large farmers.

The significant productivity and farm income gains identified above have, in some countries (notably Argentina), also made important contributions to income and employment generation in the wider economy. For example, in Argentina, the economic gains resulting from the 140% increase in the soybean area since 1995 are estimated to have contributed to the creation of 200,000 additional agriculture-related jobs (Trigo et al. 2002) and to export-led economic growth.

1.4. HOW THE ADOPTION OF PLANT BIOTECHNOLOGY HAS IMPACTED THE ENVIRONMENT

The two key aspects of environmental impact of biotech crops examined below are decreased insecticide and herbicide use, and the impact on carbon emissions and soil conservation.

1.4.1. Environmental Impacts from Changes in Insecticide and Herbicide Use

Usually, changes in pesticide use with GM crops have traditionally been presented in terms of the volume (quantity) of pesticide applied. While comparisons of total pesticide volume used in GM and non-GM crop production systems can be a useful indicator of environmental impacts, it is an imperfect measure because it does not account for differences in the specific pest control programs used in GM and non-GM cropping systems. For example, different specific chemical products used in GM versus conventional crop systems, differences in the rate of pesticides used for efficacy, and differences in the environmental characteristics (mobility, persistence, etc.) are masked in general comparisons of total pesticide volumes used.

To provide a more robust measurement of the environmental impact of GM crops, the analysis presented below includes an assessment of both pesticide active-ingredient use and the specific pesticides used via an indicator known as the *environmental impact quotient* (EIQ). This universal indicator, developed by Kovach et al. 1992 and updated annually, effectively integrates the various environmental impacts of individual pesticides into a single *field value per hectare*. This index provides a more balanced assessment of the impact of GM crops on the environment as it draws on all of the key toxicity and environmental exposure data related to individual products, as applicable to impacts on farmworkers, consumers, and ecology, and provides a consistent and comprehensive measure of environmental impact. Readers should, however, note that the EIQ is an indicator only and therefore does not account for all environmental issues and impacts.

The EIQ value is multiplied by the amount of pesticide active ingredient (AI) used per hectare to produce a field EIQ value. For example, the EIQ rating for glyphosate is 15.3. By using this rating multiplied by the amount of glyphosate used per hectare (e.g., a hypothetical example of 1.1 kg applied per hectare), the field EIQ value for glyphosate would be equivalent to 16.83/ha. In comparison, the field EIQ/ha value for a commonly used herbicide on corn crops (atrazine) is 22.9/ha.

The EIQ indicator is therefore used for comparison of the field EIQ/ha values for conventional versus GM crop production systems, with the total environmental impact or load of each system, a direct function of respective field EIQ/ha values, and the area planted to each type of production (GM vs. non-GM).

The EIQ methodology is used below to calculate and compare typical EIQ values for conventional and GM crops and then aggregate these values to a national level. The level of pesticide use in the respective areas planted for conventional and GM crops in each year was compared with the level of pesticide use that probably would otherwise have occurred if the whole crop, in each year, had been produced using conventional technology (based on the knowledge of crop advisers). This approach addresses gaps in the availability of herbicide or insecticide usage data in most countries and differentiates between GM and conventional crops. Additionally, it allows for comparisons between GM and non-GM cropping systems when GM accounts for a large proportion of the total crop planted area. For example, in the case of soybean in several countries, GM represents over 60% of the total soybean crop planted area. It is not reasonable to compare the production practices of these two groups as the remaining non-GM adopters might be farmers in a region characterized by below-average weed or pest pressures or with a tradition of less intensive production systems, and hence, below-average pesticide use.

TABLE 1.5. Impact of Changes in Use of Herbicides and Insecticides from Growing GM Crops Globally, 1996–2005

Trait	Change in Volume of Active Ingredient Used (million kg)	Change in Field EIQ Impact[a]	% Change in AI use in GM-Growing Countries	% Change in Environmental Impact in GM-Growing Countries
GM herbicide-tolerant soybean	−51.4	−4,865	−4.1	−20.0
GM herbicide-tolerant maize	−36.5	−845	−3.4	−4.0
GM herbicide-tolerant cotton	−28.6	−1,166	−15.1	−22.7
GM herbicide-tolerant canola	−6.3	−310	−11.1	−22.6
GM insect-resistant maize	−7.0	−403	−4.1	−4.6
GM insect-resistant cotton	−94.5	−4,670	−19.4	−24.3
Totals	−224.3	−12,259	−6.9	−15.3

[a]In terms of million field EIQ/ha units.

GM crops have contributed to a significant reduction in the global environmental impact of production agriculture (Table 1.5). Since 1996, the use of pesticides was reduced by 224 million kg of active ingredient, constituting a 6.9% reduction, and the overall environmental impact associated with pesticide use on these crops was reduced by 15.3%. In absolute terms, the largest environmental gain has been associated with the adoption of GM HT soybean and reflects the large share of global soybean plantings accounted for by GM soybean. The volume of herbicide use in GM soybean decreased by 51 million kg since 1996, a 4.1% reduction, and the overall environmental impact decreased by 20%. It should be noted that in some countries, such as in Argentina and Brazil, the adoption of GM HT soybean has coincided with increases in the volume of herbicides used relative to historic levels. This net increase largely reflects the facilitating role of the GM HT technology in accelerating and maintaining the switch away from conventional tillage to no/low-tillage production systems, along with their inherent environmental benefits (discussed below). This net increase in the volume of herbicides used should, therefore, be placed in the context of the reduced GHG emissions arising from this production system change (see discussion below) and the general dynamics of agricultural production system changes.

Major environmental gains have also been derived from the adoption of GM insect-resistant (IR) cotton. These gains were the largest of any crop on a per hectare basis. Since 1996, farmers have used 95.5 million kg less insecticide in GM IR cotton crops (a 19.4% reduction), and reduced the environmental impact by 24.3%. Important environmental gains have also arisen in the maize and canola sectors. In the maize sector, pesticide

TABLE 1.6. Reduction in "Environmental Impact" from Changes in Pesticide Use Associated with GM Crop Adoption by Country, 1996–2005, Selected Countries (% Reduction in Field EIQ Values)

Country	GM HT Soybean	GM HT Maize	GM HT Cotton	GM HT Canola	GM IR Maize	GM IR Cotton
USA	29	4	24	38	5	23
Argentina	21	NDA	NDA	N/A	0	4
Brazil	6	N/A	N/A	N/A	N/A	N/A
Paraguay	13	N/A	N/A	N/A	N/A	N/A
Canada	9	5	N/A	22	NDA	N/A
South Africa	7	0.44	6	N/A	2	NDA
China	N/A	N/A	N/A	N/A	N/A	28
India	N/A	N/A	N/A	N/A	N/A	3
Australia	N/A	N/A	4	N/A	N/A	22
Mexico	N/A	N/A	N/A	N/A	N/A	NDA
Spain	N/A	N/A	N/A	N/A	30	N/A

Note: Zero impact for GM IR maize in Argentina is due to the negligible (historic) use of insecticides on the Argentine maize crop. (NDA = no data available.)

use decreased by 43 million kg and the environmental impact decreased because of reduced insecticide use (4.6%) and a switch to more environmentally benign herbicides (4%). In the canola sector, farmers reduced herbicide use by 6.3 million kg (an 11% reduction) and the environmental impact has fallen by 23% because of a switch to more environmentally benign herbicides.

The impact of changes in insecticide and herbicide use at the country level (for the main GM-adopting countries) is summarized in Table 1.6.

In terms of the division of the environmental benefits associated with less insecticide and herbicide use for farmers in developing countries relative to farmers in developed countries, Table 1.7 shows that in 2005, the majority of the environmental benefits associated with lower insecticide and herbicide use have been for developing-country farmers. The vast majority of these environmental gains have been from the use of GM IR cotton and GM HT soybeans.

TABLE 1.7. GM Crop Environmental Benefits from Lower Insecticide and Herbicide Use in 2005: Developing versus Developed Countries

	Percent of Total Reduction in EI[a]	
Crop	Developed Countries	Developing Countries[b]
GM HT soybean	53	47
GM IR maize	92	8
GM HT maize	99	1
GM IR cotton	15	85
GM HT cotton	99	1
GM HT canola	100	0
Totals	46	54

[a]Environmental impact.
[b]"Developing countries", include all countries in South America.

1.4.2. Impact on Greenhouse Gas (GHG) Emissions

Reductions in the level of GHG emissions from GM crops are from two principal sources:

1. GM crops contribute to a reduction in fuel use from less frequent herbicide or insecticide applications and a reduction in the energy use in soil cultivation. For example, Lazarus and Selley (2005) estimated that one pesticide spray application uses 1.045 liters (L) of fuel, which is equivalent to 2.87 kg/ha of carbon dioxide emissions. In this analysis we used the conservative assumption that only GM IR crops reduced spray applications and ultimately GHG emissions. In addition to the reduction in the number of herbicide applications there has been a shift from conventional tillage to no/reduced tillage. This has had a marked effect on tractor fuel consumption because energy-intensive cultivation methods have been replaced with no/reduced tillage and herbicide-based weed control systems. The GM HT crop where this is most evident is GM HT soybean. Here, adoption of the technology has made an important contribution to facilitating the adoption of reduced/no-tillage (NT) farming (CTIC 2002). Before the introduction of GM HT soybean cultivars, NT systems were practiced by some farmers using a number of herbicides and with varying degrees of success. The opportunity for growers to control weeds with a nonresidual foliar herbicide as a "burndown" preseeding treatment, followed by a postemergent treatment when the soybean crop became established, has made the NT system more reliable, technically viable, and commercially attractive. These technical advantages, combined with the cost advantages, have contributed to the rapid adoption of GM HT cultivars and the near-doubling of the NT soybean area in the United States (and also a $\geq$5-fold increase in Argentina). In both countries, GM HT soybean crops are estimated to account for 95% of the NT soybean crop area. Substantial growth in NT production systems has also occurred in Canada, where the NT canola area increased from 0.8 to 2.6 million ha (equal to about half of the total canola area) between 1996 and 2005 (95% of the NT canola area is planted with GM HT cultivars). Similarly, the area planted to NT in the US cotton crop increased from 0.2 to 1 million ha over the same period (86% of which is planted to GM HT cultivars). The increase in the NT cotton area has been substantial from a base of 200,000 ha to over 1.0 million ha between 1996 and 2005. The fuel savings resulting from changes in tillage systems are drawn from estimates from studies by Jasa (2002) and CTIC (2002). The adoption of NT farming systems is estimated to reduce cultivation fuel usage by 32.52 L/ha compared with traditional conventional tillage and 14.7 L/ha compared with (the average of) reduced tillage cultivation. In turn, this results in reductions in CO_2 emissions of 89.44 and 40.43 kg/ha, respectively.
2. The use of reduced/no-tillage[6] farming systems that utilize less plowing increase the amount of organic carbon in the form of crop residue that is stored or sequestered in the soil. This carbon sequestration reduces carbon dioxide emissions to the environment. Rates of carbon sequestration have been calculated for cropping systems using

[6]*No-tillage farming* means that the ground is not plowed at all, while *reduced tillage* means that the ground is disturbed less than it would be with traditional tillage systems. For example, under a no-tillage farming system, soybean seeds are planted through the organic material that is left over from a previous crop such as corn, cotton, or wheat. No-tillage systems also significantly reduce soil erosion and hence deliver both additional economic benefits to farmers, enabling them to cultivate land that might otherwise be of limited value and environmental benefits from the avoidance of loss of flora, fauna, and landscape features.

TABLE 1.8. Impact of GM Crops on Carbon Sequestration Impact in 2005; Car Equivalents

Crop/Trait/ Country	Permanent CO_2 Savings from Reduced Fuel Use (million kg CO_2)	Average Family Car Equivalents Removed from Road per Year from Permanent Fuel Savings	Potential Additional Soil Carbon Sequestration Savings (million kg CO_2)	Average Family Car Equivalents Removed from Road per Year from Potential Additional Soil Carbon Sequestration
US: GM HT soybean	176	78,222	2,195	975,556
Argentina: GM HT soybean	546	242,667	4,340	1,928,889
Other countries: GM HT soybeans	55	24,444	435	193,333
Canada: GM HT canola	117	52,000	1,083	481,520
Global GM IR cotton	68	30,222	0	0
Totals	962	427,556	8,053	3,579,298

Note: It is assumed that an average family car produces 150 g CO_2/km. A car does an average of 15,000 km/year and therefore produces 2250 kg of CO_2 per year.

normal tillage and reduced tillage, and these were incorporated in our analysis on how GM crop adoption has significantly facilitated the increase in carbon sequestration, ultimately reducing the release of CO_2 into the atmosphere. Of course, the amount of carbon sequestered varies by soil type, cropping system, and ecoregion. In North America, the International Panel on Climate Change estimates that the conversion from conventional tillage to no-tillage systems stores between 50 and 1300 kg C/ha annually (average 300 kg C/ha per year). In the analysis presented below, a conservative savings of 300 kg C/ha per annum was applied to all no-tillage agriculture and 100 kg C/ha^{-1} year^{-1} was applied to reduced-tillage agriculture. Where some countries aggregate their no/reduced-tillage data, the reduced-tillage saving value of 100 kg C/ha^{-1} year^{-1} was used. One kilogram of carbon sequestered is equivalent to 3.67 kg of carbon dioxide. These assumptions were applied to the reduced pesticide spray applications data on GM IR crops, derived from the farm income literature review, and the GM HT crop areas using no/reduced tillage (limited to the GM HT soybean crops in North and South America and GM HT canola crop in Canada[7]).

[7]Because of the likely small-scale impact and/or lack of tillage-specific data relating to GM HT maize and cotton crops (and the US GM HT canola crop), analysis of possible GHG emission reductions in these crops have not been included in the analysis. The no/reduced-tillage areas to which these soil carbon reductions were applied were limited to the increase in the area planted to no/reduced tillage in each country since GM HT technology has been commercially available. In this way the authors have tried to avoid attributing no/reduced-tillage soil carbon sequestration gains to GM HT technology on cropping areas that were using no/reduced-tillage cultivation techniques before GM HT technology became available.

Table 1.8 summarizes the impact on GHG emissions associated with the planting of GM crops between 1996 and 2005. In 2005, the permanent CO_2 savings from reduced fuel use associated with GM crops was 0.962 billion kg. This is equivalent to removing 430,000 cars from the road for a year.

The additional soil carbon sequestration gains resulting from reduced tillage with GM crops accounted for a reduction in 8.05 billion kg of CO_2 emissions in 2005. This is equivalent to removing nearly 3.6 million cars from the roads per year. In total, the carbon savings from reduced fuel use and soil carbon sequestration in 2005 were equal to removing 4 million cars from the road (equal to 17% of all registered cars in the UK).

1.5. CONCLUSIONS

GM technology has to date delivered several specific agronomic traits that have overcome a number of production constraints for many farmers. This has resulted in improved productivity and profitability for the 8.5 million GM-adopting farmers who have applied the technology to over 87 million ha in 2005.

Since the mid-1990s, this technology has made important positive socioeconomic and environmental contributions. These have arisen despite the limited range of GM agronomic traits commercialized thus far, in a small range of crops.

GM technology has delivered economic and environmental gains through a combination of their inherent technical advances and the role of technology in the facilitation and evolution of more cost-effective and environmentally friendly farming practices. More specifically:

- The gains from the GM IR traits have mostly been delivered directly from the technology (through yield improvements, reduced production risk, and decreased insecticide use). Thus, farmers (mostly in developing countries) have been able to improve their productivity and economic returns while also practicing more environmentally friendly farming methods.
- The gains from GM HT traits have come from a combination of direct benefits (mostly cost reductions to the farmer) and the facilitation of changes in farming systems. Thus, GM HT technology (especially in soybean) has played an important role in enabling farmers to capitalize on the availability of a low-cost, broad-spectrum herbicide (glyphosate) and in turn, facilitated the move away from conventional to low/no-tillage production systems in both North and South America. This change in production system has made additional positive economic contributions to farmers (and the wider economy) and delivered important environmental benefits, notably reduced levels of GHG emissions (from reduced tractor fuel use and additional soil carbon sequestration).

The impact of GM HT traits has, however, contributed to increased reliance on a limited range of herbicides, and this raises questions about the possible future increased development of weed resistance to these herbicides. For example, some degree of reduced effectiveness of glyphosate (and glufosinate) against certain weeds has already occurred. To the extent to which this may occur in the future, there will be an increased need to include low-dose applications of other herbicides in weed control programs (commonly used in conventional production systems), which may, in turn, marginally reduce the level of net environmental and economic gains derived from the current use of GM technology.

LIFE BOX 1.1. NORMAN E. BORLAUG

Norman E. Borlaug, Retired, President of the Sasakawa Africa Association and Distinguished Professor of Agriculture at Texas A&M Univeristy; Laureate, Winner, Nobel Peace Prize, 1970; Recipient, Congressional Gold Medal 2007

Norman Borlaug

The following text is excerpted from the book by biographer Leon Hesser, *The Man Who Fed the World: Nobel Peace Prize Laureate Norman Borlaug and His Battle to End World Hunger*, Durban House Dallas, Texas (2006):

> From the day he was born in 1914, Norman Borlaug has been an enigma. How could a child of the Iowa prairie, who attended a one-teacher, one-room school; who flunked the university entrance exam; and whose highest ambition was to be a high school science teacher and athletic coach, ultimately achieve the distinction as one of the hundred most influential persons of the twentieth century? And receive the Nobel Peace Prize for averting hunger and famine? And eventually be hailed as the man who saved hundreds of millions of lives from starvation—more than any other person in history?
>
> Borlaug, ultimately admitted to the University of Minnesota, met Margaret Gibson, his wife to be, and earned B.S., M.S., and Ph.D. degrees. The latter two degrees were in plant pathology and genetics under Professor E. C. Stakman, who did pioneering research on the plant disease rust, a parasitic fungus that feeds on phytonutrients in wheat, oats, and barley. Following three years with DuPont, Borlaug went to Mexico in 1944 as a member of a Rockefeller Foundation team to help increase food production in that hungry nation where rust diseases had taken their toll on wheat yields.

Dr. Borlaug initiated three innovations that greatly increased Mexico's wheat yields. First, he and his Mexican technicians crossed thousands of varieties to find a select few that were resistant to rust disease. Next, he carried out a "shuttle breeding" program to cut in half the time it took to do the breeding work. He harvested seed from a summer crop that was grown in the high altitudes near Mexico City, flew to Obregon to plant the seed for a winter crop at sea level. Seed from that crop was flown back to near Mexico City and planted for a summer crop. Shuttle breeding not only worked, against the advice of fellow scientists, but serendipitously the varieties were widely adapted globally because it had been grown at different altitudes and latitudes and during different day lengths.

But, there was a problem. With high levels of fertilizer in an attempt to increase yields, the plants grew tall and lodged. For his third innovation, then, Borlaug crossed his rust-resistant varieties with a short-strawed, heavy tillering Japanese variety. Serendipity squared. The resulting seeds were responsive to heavy applications of fertilizer without lodging. Yields were six to eight times higher than for traditional varieties in Mexico. It was these varieties, introduced in India and Pakistan in the mid-1960s, which stimulated the Green Revolution that took those countries from near-starvation to self-sufficiency. For this remarkable achievement, Dr. Borlaug was awarded the Nobel Peace Prize in 1970.

In 1986, Borlaug established the World Food Prize, which provides $250,000 each year to recognize individuals in the world who are deemed to have done the most to increase the quantity or quality of food for poorer people. A decade later, the World Food Prize Foundation added a Youth Institute as a means to get young people interested in the world food problem. High school students are invited to submit essays on the world food situation. Authors of the 75 best papers are invited to read them at the World Food Prize Symposium in Des Moines in mid-October each year. From among these, a dozen are sent for eight weeks to intern at agricultural research stations in foreign countries. By the summer of 2007, approximately 100 Youth Institute interns had returned enthusiastically from those experiences and all are on track to become productively involved. This is an answer to Norman Borlaug's dream.

Borlaug has continually advocated increasing crop yields as a means to curb deforestation. In addition to his being recognized as having saved millions of people from starvation, it could be said that he has saved more habitat than any other person.

When Borlaug was born in 1914, the world's population was 1.6 billion. During his lifetime, population has increased four times, to 6.5 billion. Borlaug is often asked, "How many more people can the Earth feed?" His usual response: "I think the Earth can feed 10 billion people, IF, and this is a big IF, we can continue to use chemical fertilizer and there is public support for the relatively new genetic engineering research in addition to conventional research."

To those who advocate only organic fertilizer, he says, "For God's sake, let's use all the organic materials we can muster, but don't tell the world that we can produce enough food for 6.5 billion people with organic fertilizer alone. I figure we could produce enough food for only 4 billion with organics alone."

One of Borlaug's dreams, through genetic engineering, is to transfer the rice plant's resistance to rust diseases to wheat, barley, and oats. He is deeply concerned about a recent outbreak of rust disease in sub-Saharan Africa which, if it gets loose, can devastate wheat yields in much of the world.

Since 1984, Borlaug has served each fall semester at Texas A&M University as distinguished professor of international agriculture. In 1999, the university's Center for Southern Crop Improvement was named in his honor.

As President of the Sasakawa Africa Association (SAA) since 1986, Borlaug has demonstrated how to increase yields of wheat, rice, and corn in sub-Saharan Africa. To focus on food, population and agricultural policy, Jimmy Carter initiated Sasakawa-Global 2000, a joint venture between the SAA and the Carter Center's Global 2000 program.

Norman Borlaug has been awarded more than fifty honorary doctorates from institutions in eighteen countries. Among his numerous other awards are the U.S. Presidential Medal of Freedom (1977); the Rotary International Award (2002); the National Medal of Science (2004); the Charles A. Black Award for contributions to public policy and the public understanding of science (2005); the Congressional Gold Medal (2006); and the Padma Vibhushan, the Government of India's second highest civilian award (2006).

The Borlaug family includes son William, daughter Jeanie, five grandchildren and four great grandchildren. Margaret Gibson Borlaug, who had been blind in recent years, died on March 8, 2007 at age 95.

LIFE BOX 1.2. MARY-DELL CHILTON

Mary-Dell Chilton, Scientific and Technical Principal Fellow, Syngenta Biotechnology, Inc.; Winner of the Rank Prize for Nutrition (1987), and the Benjamin Franklin Medal in Life Sciences (2001); Member, National Academy of Sciences

Mary-Dell Chilton in the Washington University (St. Louis) Greenhouse 1982 with tobacco, the white rat of the plank kingdom.

I entered the University of Illinois in the fall of 1956, the autumn that Sputnik flew over. My major was called the "Chemistry Curriculum," and was heavy on science and light on liberal arts. When I entered graduate school in 1960 as an organic chemistry major, still at the University of Illinois, I took a minor in microbiology (we were required to minor in something. . .). To my astonishment I found a new love: in a course called "The Chemical Basis of Biological Specificity" I learned about the DNA double helix, the genetic code, bacterial genetics, mutations and bacterial transformation. I was hooked! I found that I could stay in the Chemistry Department (where I had passed prelims, a grueling oral exam) and work on DNA under guidance of a new thesis advisor, Ben Hall, a professor in physical chemistry. When Hall took a new position in the Department of Genetics at the University of Washington, I followed him. This led to a new and fascinating dimension to my education. My thesis was on transformation of *Bacillus subtilis* by single-stranded DNA,

As a postdoctoral fellow with Dr. Brian McCarthy in the Microbiology Department at the University of Washington, I did further work on DNA of bacteria, mouse, and finally maize. I became proficient in all of the then-current DNA technology. During this time I married natural products chemist Prof. Scott Chilton and we had two sons to whom I was devoted. But that was not enough. It was time to start my career!

Two professors (Gene Nester in microbiology and Milt Gordon in biochemistry) and I (initially as an hourly employee) launched a collaborative project on *Agrobacterium tumefaciens* and how it causes the plant cancer "crown gall." In hindsight it was no accident that we three represented at least three formal disciplines (maybe four or five, if you count my checkered career). Crown gall biology would involve us in plants, microbes, biochemistry, genetics, protein chemistry, natural products chemistry (in collaboration with Scott) and plant tissue culture. The multifaceted nature of the problem bound us together.

My first task was to write a research grant application to raise funds for my own salary. My DNA hybridization proposal was funded. Grant money flowed in the wake of Sputnik. Our primary objective was to determine whether DNA transfer from the bacterium to the plant cancer cells was indeed the basis of the disease, as some believed and others disputed. We disputed this continually amongst ourselves, often switching sides! This was the start of a study that has extended over my entire career. While we hunted for bacterial DNA, competitors in Belgium discovered that virulent strains of *Agrobacterium* contained enormous plasmids (circular DNA molecules) which we now know as Ti (tumor-inducing) plasmids. Redirecting our analysis, we found that gall cells contained not the whole Ti plasmid but a sector of it large enough to encompass 10–20 genes.

Further studies in several laboratories world-wide showed that this transferred DNA, T-DNA, turned out to be in the nuclei of the plant cells, attached to the plant's own chromosomal DNA. It was behaving as if it were plant genes, encoding messenger RNA and proteins in the plant. Some proteins brought about the synthesis of plant growth hormones that made the plant gall grow. Others caused the plant to synthesize, from simple amino acids and sugars or keto acids, derivatives called opines, some of which acted as bacterial hormones, inducing conjugation of the plasmid from one *Agrobacterium* to another. The bacteria could live on these opines, too, a feat not shared by most other bacteria. Thus, a wonderfully satisfying biological picture emerged. We could envision *Agrobacterium* as a microscopic genetic engineer, cultivating plant cells for their own benefit.

At that time only a dreamer could imagine the possibility of exploiting *Agrobacterium* to put genes of our choice into plant cells for crop improvement. There were many obstacles to overcome. We had to learn how to manipulate genes on the Ti plasmid, how to remove the bad ones that caused the plant cells to be tumorous and how to introduce new genes. We had to learn what defined T-DNA on the plasmid. It turned out that *Agrobacterium* determined what part of the plasmid to transfer by recognizing a 25 basepair repeated sequence on each end. One by one, as a result of research by several groups around the world, the problems were solved. The Miami Winter Symposium in January 1983 marked the beginning of an era. Presentations by Belgian, German and two U.S. groups, including mine at Washington University in St. Louis, showed that each of the steps in genetic engineering was in place, at least for (dicotyledonous) tobacco and petunia plants. Solutions were primitive by today's standards, but in principle it was clear that genetic engineering was feasible; *Agrobacterium* could be used to transform a number of dicots.

I saw that industry would be a better setting than my university lab for the next step: harnessing the Ti plasmid for crop improvement. When a Swiss multinational company, CIBA–Geigy, offered me the task of developing from scratch an agricultural biotechnology lab to be located in North Carolina where I had grown up, it seemed tailor made for me. I joined this company in 1983. CIBA–Geigy and I soon found that we had an important incompatibility: while I was good at engineering genes into (dicotyledonous) tobacco plants, the company's main seed business was (monocotyledonous) hybrid corn seed. Nobody knew whether *Agrobacterium* could transfer T-DNA. This problem was solved and maize is now transformable by either *Agrobacterium* or the "gene gun" technique. Our company was first to the market with Bt maize.

The company underwent mergers and spinoffs, arriving at the new name of

Syngenta a few years ago. My role also evolved. After 10 years of administration, I was allowed to leave my desk and go back to the bench. I began working on "gene targeting," which means finding a way to get T-DNA inserts to go where we want them in the plant chromosomal DNA, rather than random positions it goes of its own accord.

Transgenic crops now cover a significant fraction of the acreage of soybeans and corn. In addition, transgenic plants serve as a research tool in plant biology. *Agrobacterium* has already served us well, both in agriculture and in basic science. New developments in DNA sequencing and genomics will surely lead to further exploitation of transgenic technology for the foreseeable future.

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