CHAPTER 1

# The Impact of Biotechnology on Plant Agriculture

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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 1994, biotechnology has revolutionized plant agriculture. In the United States, between 80 and 90% of the maize (corn), soybean, cotton, and canola crops 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 the environment?

## 1.1. INTRODUCTION

The technology of genetic modification (GM, also stands for "genetically modified"), which consists of genetic engineering and also known as genetic transformation, has now been utilized globally on a widespread commercial basis for 18 years; and by 2012, 17.3 million farmers in 28 countries had planted 160 million hectares of crops using this technology. These milestones provide an opportunity to critically assess the impact of this technology on global agriculture. This chapter therefore examines specific global socioeconomic impacts on farm income and environmental impacts with respect to pesticide usage and greenhouse gas (GHG) emissions of the technology. Further details can be found in Brookes and Barfoot (2014a, b).

*Plant Biotechnology and Genetics: Principles, Techniques, and Applications*, Second Edition. Edited by C. Neal Stewart, Jr.

## 1.2. CULTIVATION OF BIOTECHNOLOGY (GM) CROPS

Although the first commercial GM crops were planted in 1994 (tomatoes), 1996 was the first year in which a significant area of crops containing GM traits were planted (1.66 million hectares). Since then, there has been a dramatic increase in plantings, and by 2012 the global planted area reached over 160.4 million hectares.

Almost all of the global GM crop area derives from soybean, maize (corn), cotton, and canola (Fig. 1.1). In 2012, GM soybean accounted for the largest share (49%) of total GM crop cultivation, followed by maize (32%), cotton (14%), 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 (73%) in 2012 (i.e., non-GM soybean accounted for 27% of global soybean acreage in 2012). For the other three main crops, the GM shares in 2012 of total crop production were 29% for maize, 59% for cotton, and 26% for canola (i.e., the majority of global plantings of maize and canola continued to be non-GM in 2012). The trend in plantings of GM crops (by crop) from 1996 to 2012 is shown in Figure 1.2. In terms of the type of biotechnology trait planted, Figure 1.3 shows that GM herbicide-tolerant soybeans dominate, accounting for 38% of the total, followed by insect-resistant (largely Bt) maize, herbicide-tolerant maize, and insect-resistant cotton with respective shares of 26, 19, and 11%. It is worth noting that the total number of plantings by trait produces a higher global planted area (209.2 million hectares) than the global area by crop (160.4 million hectares) 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).

In total, GM herbicide-tolerant (GM HT) crops account for 63%, and GM insect-resistant (GM IR) crops account for 37% 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 2012

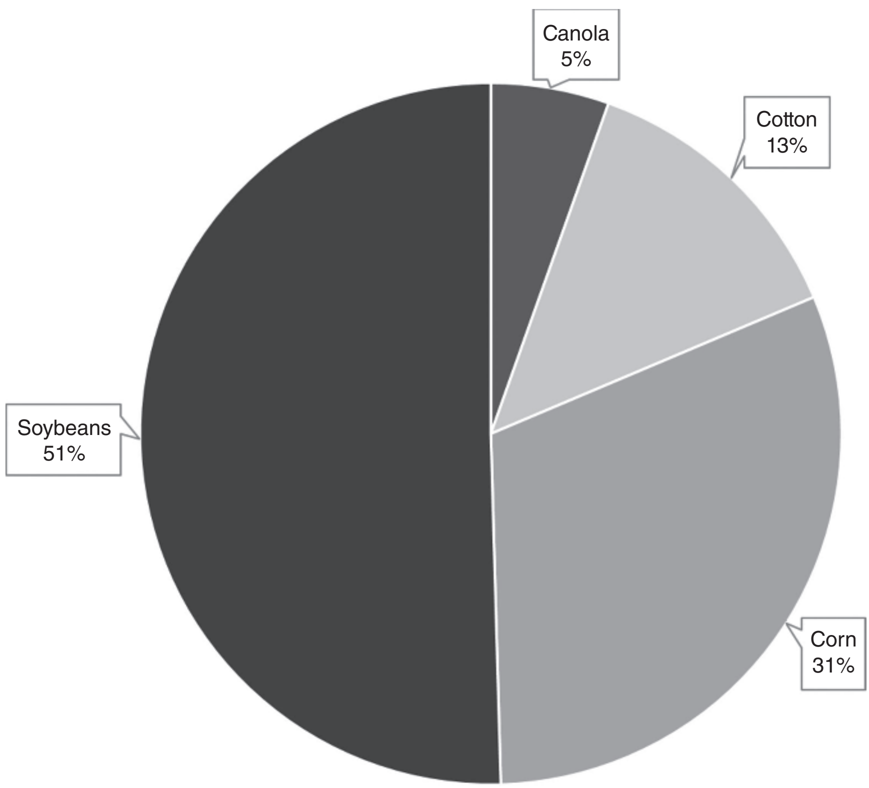


**Figure 1.1.** Global GM crop plantings in 2012 by crop (base area: 160.4 million hectare). (*Sources*: ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio.)

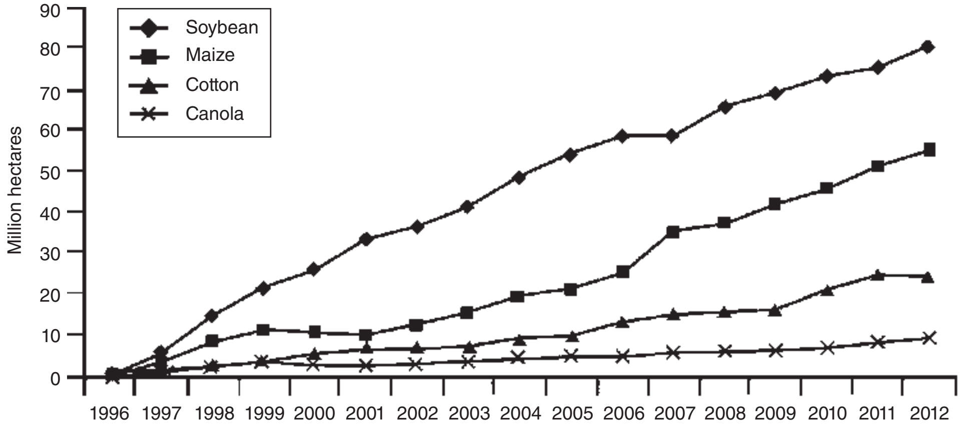


**Figure 1.2.** Global GM crop plantings by crop 1996–2012. (*Sources*: ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio.)

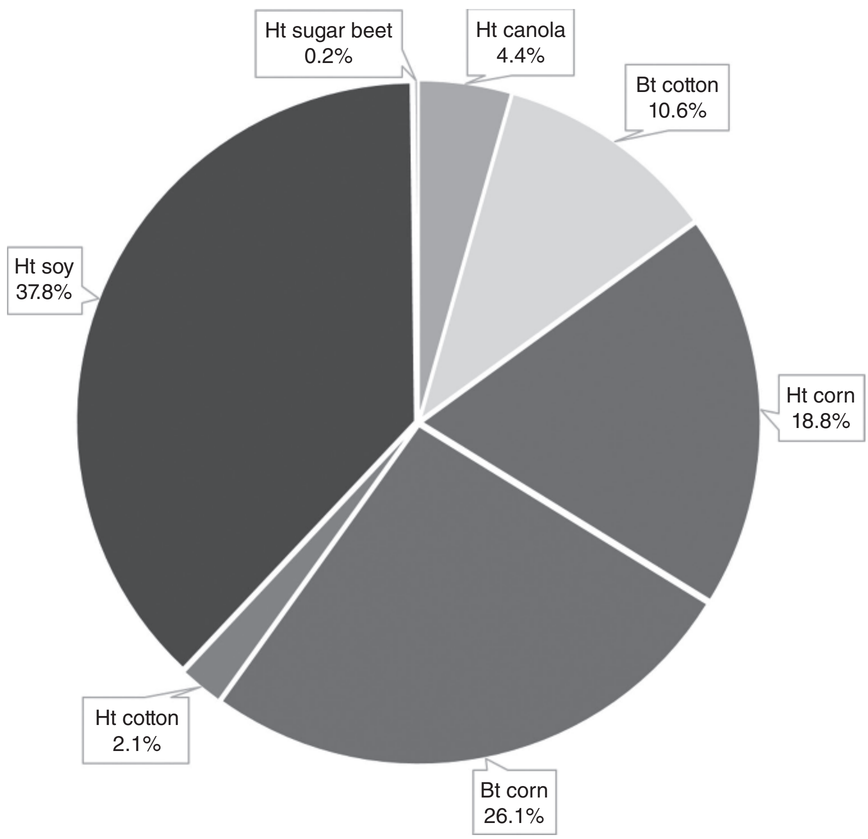


**Figure 1.3.** Global GM crop plantings by main trait and crop: 2012. (*Sources*: Various, including ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio.)

(40%: 64.1 million hectares), followed by Brazil (37.2 million hectares: 23% of the global total) and Argentina (14%: 23.1 million hectares). The other main countries planting GM crops in 2012 were India, Canada, and China (Fig. 1.4). In 2012, there were also additional GM crop plantings of papaya (395 hectares), squash (2000 hectares), alfalfa (425,000 hectares), and sugar

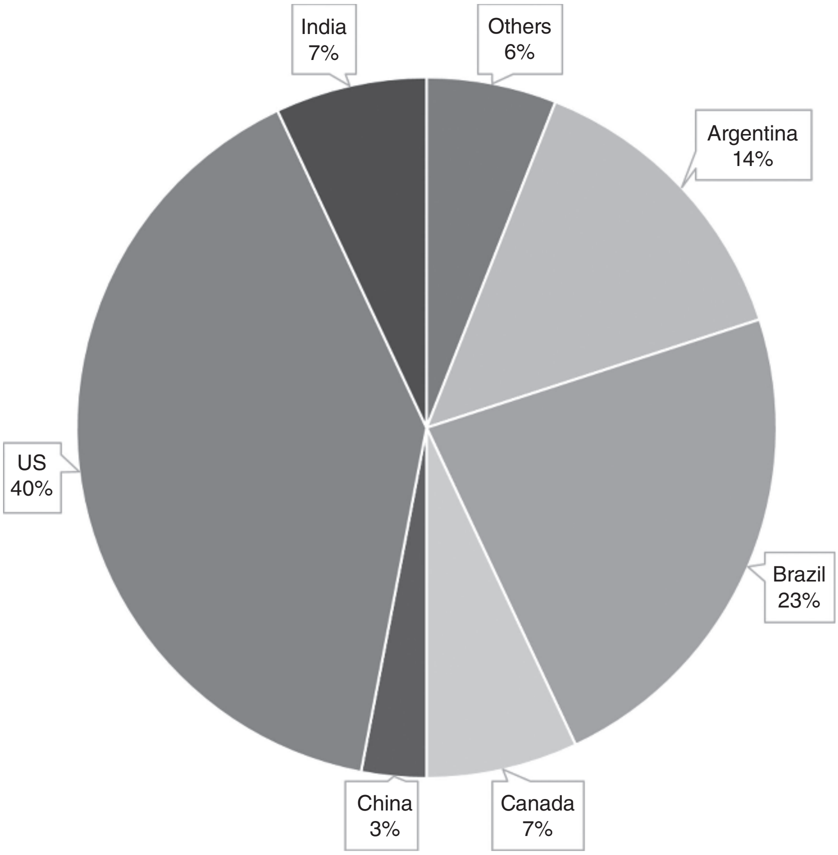


**Figure 1.4.** Global GM crop plantings 2012 by country. (*Sources*: ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio.)

beet (490,000 hectares) in the United States, of papaya (5000 hectares) in China and of sugar beet (13,500 hectares) in Canada.

## 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 2012, the direct global farm income benefit from GM crops was $18.8 billion. This is equivalent to having added 5.6% 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 $116.6 billion, directly because of the adoption of GM crop technology.

The largest gains in farm income in 2012 have arisen in the maize sector, largely from yield gains. The $6.7 billion additional income generated by GM IR maize in 2012 has been equivalent to adding 6.6% to the value of the crop in the GM crop-growing countries, or adding the equivalent of 3% to the $226 billion value of the global maize crop in 2012. Cumulatively since 1996, GM IR technology has added $32.3 billion to the income of global maize farmers.

Substantial gains have also arisen in the cotton sector through a combination of higher yields and lower costs. In 2012, cotton farm income levels in the GM-adopting countries increased by

**TABLE 1.1. Global Farm Income Benefits from Growing GM Crops 1996–2012 (Million US $)**

| Trait | Increase in farm income 2012 | Increase in farm income 1996–2012 | Farm income benefit in 2012 as percentage of total value of production of these crops in GM adopting countries | Farm income benefit in 2012 as percentage of total value of global production of crop |
|---|---|---|---|---|
| GM herbicide-tolerant soybeans | 4,797.9 | 37,008.6 | 4.4 | 4.0 |
| GM herbicide-tolerant maize | 1,197.9 | 5,414.7 | 1.2 | 0.5 |
| GM herbicide-tolerant cotton | 147.2 | 1,371.6 | 0.4 | 0.3 |
| GM herbicide-tolerant canola | 481.0 | 3,664.4 | 4.9 | 1.3 |
| GM insect-resistant maize | 6,727.8 | 32,317.2 | 6.6 | 3.0 |
| GM insect-resistant cotton | 5,331.3 | 36,317.2 | 13.1 | 11.2 |
| Others | 86.3 | 496.7 | N/A | N/A |
| Total | 18,769.4 | 116,590.4 | 6.8 | 5.6 |

*Notes*: All values are nominal. Others = Virus resistant papaya and squash and herbicide-tolerant sugar beet. 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 yield, crop quality, and key variable costs of production (e.g., payment of seed premia, impact on crop protection expenditure). N/A = not applicable.

$5.5 billion; and since 1996, the sector has benefited from an additional $37.7 billion. The 2012 income gains are equivalent to adding 13.5% to the value of the cotton crop in these countries, or 11.5% to the $47 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 soybean and canola sectors. The GM HT technology in soybeans has boosted farm incomes by $4.8 billion in 2012, and since 1996 has delivered over $37 billion of extra farm income. In the canola sector (largely North American) an additional $3.66 billion has been generated (1996–2012).

Overall, the economic gains derived from planting GM crops have been of two main types: (a) increased yields (associated mostly with GM IR technology) and (b) 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 farm income benefit arising from GM HT soybeans in South America (Argentina, Bolivia, Brazil, Paraguay, and Uruguay), GM IR cotton in China and India, and a range of GM cultivars in the United States. It also illustrates the growing level of farm income benefits being obtained in South Africa, the Philippines, Mexico, and Colombia from planting GM crops.

In terms of the division of the economic benefits, it is interesting to note that farmers in developing countries derived in 2012 (46.2%) 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.[1]

[1] The author acknowledges that the classification of different countries into “developing” or “developed” 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 (2012)].

**TABLE 1.2. GM Crop Farm Income Benefits During 1996–2012 in Selected Countries (Million US $)**

| | GM HT soybeans | GM HT maize | GM HT cotton | GM HT canola | GM IR maize | GM IR cotton | Total |
|---|---|---|---|---|---|---|---|
| United States | 16,668.7 | 3752.3 | 975.8 | 268.3 | 26,375.9 | 4,046.7 | 52,087.7 |
| Argentina | 13,738.5 | 766.7 | 107.0 | N/A | 495.2 | 456.4 | 15,563.8 |
| Brazil | 4,825.6 | 703.4 | 92.5 | N/A | 2,761.7 | 13.3 | 8,396.5 |
| Paraguay | 828 | N/A | N/A | N/A | N/A | N/A | 828.0 |
| Canada | 358 | 81.3 | N/A | 3368.8 | 1,042.9 | N/A | 4,851.0 |
| South Africa | 9.1 | 4.1 | 3.2 | N/A | 1,100.6 | 34.2 | 1,151.2 |
| China | N/A | N/A | N/A | N/A | N/A | 15,270.4 | 15,270.4 |
| India | N/A | N/A | N/A | N/A | N/A | 14,557.1 | 14,557.1 |
| Australia | N/A | N/A | 78.6 | 27.3 | N/A | 659.6 | 765.5 |
| Mexico | 5.0 | N/A | 96.4 | N/A | N/A | 136.6 | 238.0 |
| Philippines | N/A | 104.7 | N/A | N/A | 273.6 | N/A | 378.3 |
| Romania | 44.6 | N/A | N/A | N/A | N/A | N/A | 44.6 |
| Uruguay | 103.8 | N/A | N/A | N/A | 17.6 | N/A | 121.4 |
| Spain | N/A | N/A | N/A | N/A | 176.3 | N/A | 176.3 |
| Other EU | N/A | N/A | N/A | N/A | 18.8 | N/A | 18.8 |
| Colombia | N/A | 1.7 | 18.1 | N/A | 47.4 | 15.4 | 826.6 |
| Bolivia | 432.2 | N/A | N/A | N/A | N/A | N/A | 432.2 |
| Burma | N/A | N/A | N/A | N/A | N/A | 215.4 | 215.4 |
| Pakistan | N/A | N/A | N/A | N/A | N/A | 725.1 | 725.1 |
| Burkina Faso | N/A | N/A | N/A | N/A | N/A | 186.9 | 186.9 |
| Honduras | N/A | N/A | N/A | N/A | 6.9 | N/A | 6.9 |

*Notes*: All values are nominal. Farm income calculations are net farm income changes after inclusion of impacts on yield, crop quality, and key variable costs of production (e.g., payment of seed premia, impact on crop protection expenditure). N/A = not applicable. US total figure also includes $491 million for other crops/traits (not included in the table). Also not included in the table is $5.5 million extra farm income from GM HT sugar beet in Canada.

**TABLE 1.3. GM Crop Farm Income Benefits, 2012: Developing Versus Developed Countries (Million US $)**

| | Developed | Developing |
|---|---|---|
| GM HT soybeans | 2,955.4 | 1842.5 |
| GM HT maize | 654.0 | 543.9 |
| GM HT cotton | 71.4 | 75.8 |
| GM HT canola | 481.0 | 0 |
| GM IR maize | 5,327.5 | 1400.3 |
| GM IR cotton | 530.7 | 4800.7 |
| GM virus-resistant papaya and squash and GM HT sugar beet | 86.3 | 0 |
| Total | 10,106.3 | 8663.2 |

*Note*: Developing countries = All countries in South America, Mexico, Honduras, Burkina Faso, India, China, the Philippines, and South Africa.

Examination of the cost farmers pay for accessing GM technology relative to the total gains derived shows that across the four main GM crops, the total cost was equal to about 23% of the total farm income gains (Table 1.4). For farmers in developing countries, the total cost is equal to about 21% of total farm income gains, while for farmers in developed countries the cost is about 25% of the total farm income gain. Although circumstances vary between countries, the higher share of total technology gains accounted for by farm income gains in developing countries, relative to the farm income share in developed countries, reflects factors such as weaker provision and enforcement of intellectual property rights in developing countries and the higher average

**TABLE 1.4. Cost of Accessing GM Technology Relative to Total Farm Income Benefits (US Millions) 2012**

| | Tech costs: all farmers | Farm income gain: all farmers | Total benefit of technology to farmers and seed supply chain | Cost of technology: developing countries | Farm income gain: developing countries | Total benefit of technology to farmers and seed supply chain: developing countries |
|---|---|---|---|---|---|---|
| GM HT soy | 1528.1 | 4,797.9 | 6,326.0 | 998.7 | 1842.5 | 2,841.2 |
| GM HT maize | 1059.4 | 1,197.9 | 2,257.3 | 364.5 | 543.9 | 908.4 |
| GM HT cotton | 295.0 | 147.2 | 442.2 | 22.2 | 75.8 | 98.0 |
| GM HT canola | 161.2 | 481.0 | 642.2 | N/A | N/A | N/A |
| GM IR maize | 1800.8 | 6,727.8 | 8,528.6 | 512.3 | 1400.3 | 1,912.6 |
| GM IR cotton | 720.7 | 5,331.3 | 6,052.0 | 422.7 | 4800.7 | 5,223.4 |
| Others | 76.2 | 86.3 | 162.5 | N/A | N/A | N/A |
| *Total* | 5641.4 | 18,769.4 | 24,410.8 | 2320.4 | 8663.2 | 10,983.6 |

N/A = not applicable. Cost of accessing technology based on the seed premiums paid by farmers for using GM technology relative to its conventional equivalents.

level of farm income gain on a per-hectare basis derived by developing country farmers relative to developed country farmers.

In addition to the tangible and quantifiable impacts on farm profitability presented earlier, 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 later in the text as being important influences for the adoption of the technology.

## 1.4. GM'S EFFECTS ON CROP PRODUCTION AND FARMING

Based on the yield impacts used in the direct farm income benefit calculations discussed earlier and taking account of the second soybean crop facilitation in South America, GM crops have added important volumes to global production of maize, cotton, canola, and soybeans since 1996 (Table 1.5).

The GM IR traits, used in maize and cotton, have accounted for 97.1% of the additional maize production and 99.3% of the additional cotton production. Positive yield impacts from the use of this technology have occurred in all user countries (except for GM IR cotton in Australia[2]) when compared to average yields derived from crops using conventional technology (i.e., application of insecticides and seed treatments). The average yield impact across the total area planted to these traits over the 17 years since 1996 has been +10.4% for maize and +16.1% for cotton.

As indicated earlier, the primary impact of GM HT technology has been to provide more cost-effective (less-expensive) and easier weed control, as opposed to improving yields. The improved weed control has, nevertheless, delivered higher yields in some countries. The main source of additional production from this technology has been via the facilitation of no-tillage production system, shortening the production cycle and how it has enabled many farmers in South America to plant a crop of soybeans immediately after a wheat crop in the same growing season. This second crop, additional to traditional soybean production, has added 114.3 million tonnes to soybean production in Argentina and Paraguay between 1996 and 2012 (accounting for 93.5% of the total GM-related additional soybean production).

[2] This reflects the levels of *Heliothis*/*Helicoverpa* (boll and bud worm pests) pest control previously obtained with intensive insecticide use. The main benefit and reason for adoption of this technology in Australia has arisen from significant cost savings (on insecticides) and the associated environmental gains from reduced insecticide use.

**TABLE 1.5. Additional Crop Production Arising from Positive Yield Effects of GM Crops**

| | 1996–2012 additional production (million tonnes) | 2012 additional production (million tonnes) |
|---|---|---|
| Soybeans | 122.3 | 12.0 |
| Maize | 231.4 | 34.1 |
| Cotton | 18.2 | 2.4 |
| Canola | 6.6 | 0.4 |
| Sugar beet | 0.6 | 0.15 |

*Note*: GM HT sugar beet has been commercialized only in the United States and Canada since 2008.

## 1.5. HOW THE ADOPTION OF PLANT BIOTECHNOLOGY HAS IMPACTED THE ENVIRONMENT

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

### 1.5.1. 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 in the following text 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/hectare. In comparison, the field EIQ/hectare value for a commonly used herbicide on corn crops (atrazine) is 22.9/hectare.

The EIQ indicator is therefore used for comparison of the field EIQ/hectare 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/hectare values, and the area planted to each type of production (GM vs. non-GM).

The EIQ methodology is used in the following 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.

GM crops have contributed to a significant reduction in the global environmental impact of production agriculture (Table 1.6). Since 1996, the use of pesticides was reduced by 503 million kg of AI, constituting an 8.8% reduction, and the overall environmental impact associated with pesticide use on these crops was reduced by 18.7%. In absolute terms, the largest environmental gain has been associated with the adoption of GM IR technology. GM IR cotton has contributed a 25.6% reduction in the volume of AI used and a 28.2% reduction in the EIQ indicator (1996–2012) due to the significant reduction in insecticide use that the technology has facilitated, in what has traditionally been an intensive user of insecticides. Similarly, the use of GM IR technology in maize has led to important reductions in insecticide use, with associated environmental benefits.

The volume of herbicides used in GM maize crops also decreased by 203 million kg (1996–2012), a 9.8% reduction, whilst the overall environmental impact associated with herbicide use on these crops decreased by a significantly larger 13.3%. This highlights the switch in herbicides used with most GM HT crops to AIs with a more environmentally benign profile than the ones generally used on conventional crops.

**TABLE 1.6. Impact of Changes in the Use of Herbicides and Insecticides from Global Cultivation of GM Crops, Including Environmental Impact Quotient (EIQ), 1996–2012**

| Trait | Change in mass of active ingredient used (million kg) | Change in field EIQ (in terms of million field EIQ/ hectare units) | Percentage change in AI use on GM crops | Percentage change in environmental impact associated with herbicide and insecticide use on GM crops | Area GM trait 2012 (million hectare) |
|---|---|---|---|---|---|
| GM herbicide-tolerant soybeans | −4.7 | −6,654 | −0.2 | −15.0 | 79.1 |
| GM herbicide-tolerant maize | −203.2 | −6,025 | −9.8 | −13.3 | 38.5 |
| GM herbicide-tolerant canola | −15.0 | −509 | −16.7 | −26.6 | 8.6 |
| GM herbicide-tolerant cotton | −18.3 | −460 | −6.6 | −9.0 | 4.4 |
| GM insect-resistant maize | −57.6 | −2,215 | −47.9 | −45.1 | 42.3 |
| GM insect-resistant cotton | −205.4 | −9,256 | −25.6 | −28.2 | 22.1 |
| GM herbicide-tolerant sugar beet | +1.3 | −2 | +29.3 | −2.0 | 0.51 |
| *Totals* | −503.1 | −25,121 | −8.8 | −18.7 | |

**TABLE 1.7. Changes in Environmental Impact Quotient (EIQ) form GM Crops and Associated Changes in Associated Insecticide and Herbicide Use in 2012: Developing versus Developed Countries**

| | Change in field EIQ (in terms of million field EIQ/hectare units): developed countries | Change in field EIQ (in terms of million field EIQ/hectare units): developing countries |
|---|---|---|
| GM HT soybeans | −4,773.9 | −1,880.2 |
| GM HT maize | −5,585.9 | −438.8 |
| GM HT cotton | −351.0 | −109.3 |
| GM HT canola | −509.1 | 0 |
| GM IR maize | −1,574.4 | −640.8 |
| GM IR cotton | −805.5 | −8,451.0 |
| GM HT sugar beet | −2 | 0 |
| Total | −13,601.8 | −11,520.1 |

Important environmental gains have also arisen in the soybean and canola sectors. In the soybean sector, herbicide use decreased by 4.7 million kg (1996–2012) and the associated environmental impact of herbicide use on this crop area decreased, from a switch to more environmentally benign herbicides (−15%). In the canola sector, farmers reduced herbicide use by 15 million kg (a 16.7% reduction) and the associated environmental impact of herbicide use on this crop area fell by 26.6% (from switching to more environmentally benign herbicides).

In terms of the division of the environmental benefits associated with less insecticide and herbicide use for farmers in developed countries relative to farmers in developing countries, Table 1.7 shows a 54 : 46% split of the environmental benefits (1996–2012), respectively, in developed (54%) and developing countries (46%). About three-quarters (73%) of the environmental gains in developing countries have been from the use of GM IR cotton.

It should, however, be noted that in some regions where GM HT crops have been widely grown, some farmers have relied too much on the use of single herbicides, such as glyphosate, to manage weeds in GM HT crops and this has contributed to the evolution and spread of weed resistance. There are currently 31 weed species recognized as exhibiting resistance to glyphosate worldwide, of which several are not associated with glyphosate-tolerant crops (www.weedscience.org). For example, there are currently 14 weeds recognized in the United States as exhibiting resistance to glyphosate, of which two are not associated with glyphosate tolerant crops. In the United States, the affected area is currently within a range of 15–40% of the total area annually devoted to maize, cotton, canola, soybeans, and sugar beet (the crops in which GM HT technology is used).

In recent years, there has also been a growing consensus among weed scientists of a need for changes in the weed management programs in GM HT crops, because of the apparent increase of evolution glyphosate-resistant weeds. Growers of GM HT crops are increasingly being advised to be more proactive and include other herbicides (with different and complementary modes of action) in combination with glyphosate in their integrated weed management systems, even where instances of weed resistance to glyphosate have not been found.

This proactive, diversified approach to weed management is the principal strategy for avoiding the emergence of HR weeds in GM HT crops. It is also the main way of tackling weed resistance in conventional crops. A proactive weed management program also generally requires using less herbicide, has a better environmental profile, and is more economical than a reactive weed management program.

At the macrolevel, the adoption of both reactive and proactive weed management programs in GM HT crops has already begun to influence the mix, total amount and overall environmental profile of herbicides applied to GM HT soybeans, cotton, maize, and canola, and this is reflected in the data presented in this chapter.

### 1.5.2. Impact on GHG Emissions

The reduction in the levels of GHG emissions from GM crops are from the following 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 (2012) estimated that one pesticide spray application uses 0.84 l of fuel per hectare, which is equivalent to 2.24 kg/hectare 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 (NT) and herbicide-based weed control systems, which has had a marked effect on tractor fuel consumption. The GM HT crop where this is most evident is GM HT soybean and where the GM HT soybean and maize rotation is widely practiced, for example in the United States. Here, adoption of the technology has made an important contribution to facilitating the adoption of NT farming (CTIC 2002, American Soybean Association 2001). 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 ≥sevenfold 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 8 million hectares a (equal to about 90% of the total canola area) between 1996 and 2012 (95% of the NT canola area is planted with GM HT cultivars). The area planted to NT in the US cotton crop increased from 0.2 to 1 million hectare 1996–2005 (86% of which is planted to GM HT cultivars), although the NT cotton area has not risen above about 25% of the total crop. The fuel savings used in this chapter are drawn from a review of literature including Jasa (2002), CTIC (2002), University of Illinois (2006), USDA Energy Estimator (USDA 2013b), Reeder (2010), and the USDA Comet-VR model (USDA 2013a). It is assumed that the adoption of NT farming systems in soybean production reduces cultivation and seedbed preparation fuel usage by 27.12 l/hectare compared with traditional conventional tillage and in the case of RT (mulch till) cultivation by 10.39 l/hectare. In the case of maize, NT results in a saving of 24.41 l/hectare and 7.52 l/hectare in the case of RT compared with conventional intensive tillage. These are conservative estimates and are in line with the USDA Energy Estimator for soybeans and maize.

   The adoption of NT and RT systems in respect of fuel use therefore results in reductions of carbon dioxide emissions of 72.41 kg/hectare and 27.74 kg/hectare respectively for soybeans and 65.17 kg/hectare and 20.08 kg/hectare for maize.
2. The use of NT[3] farming systems that utilize less plowing increases the amount of organic carbon in the form of crop residue that is stored or sequestered in the soil. This carbon

[3] NT 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 an NT farming system, soybean seeds are planted through the organic material that is left over from a previous crop such as corn, cotton, or wheat. NT 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.

sequestration reduces carbon dioxide emissions to the environment. Rates of carbon sequestration have been calculated for cropping systems using 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.

Drawing on the literature and models referred to earlier, the analysis presented in the following text has several assumptions by country and crop. For the United States, the soil carbon sequestered by tillage system for maize in continuous rotation with soybeans is assumed to be a net sink of 250 kg of carbon/hectare/year based on NT systems store 251 kg of carbon/hectare/year, RT systems store 75 kg of carbon/hectare/, and CT systems store 1 kg of carbon/hectare/year. For the United States, the soil carbon sequestered by tillage system for soybeans in a continuous rotation with maize is assumed to be a net sink of 100 kg of carbon/hectare/year based on NT systems release 45 kg of carbon/hectare/year, RT systems release 115 kg of carbon/hectare/year, and CT systems release 145 kg of carbon/hectare/year.

For Argentina and Brazil, soil carbon retention is 275 kg carbon/hectare/year for NT soybean cropping and CT systems release 25 kg carbon/hectare/year (a difference of 300 kg carbon/hectare/year).

Table 1.8 summarizes the impact on GHG emissions associated with the planting of GM crops between 1996 and 2012. In 2012, the permanent $CO_2$ savings from reduced fuel use associated with GM crops was 2111 million kg. This is equivalent to removing 900,000 cars from the road for a year.

**TABLE 1.8. Impact of GM Crops on Carbon Sequestration Impact in 2012; Car Equivalents**

| Crop/trait/ country | Permanent carbon dioxide savings arising from reduced fuel use (million kg of carbon dioxide) | Permanent fuel savings: as average family car equivalents removed from the road for a year ('000s) | Potential additional soil carbon sequestration savings (million kg of carbon dioxide) | Soil carbon sequestration savings: as average family car equivalents removed from the road for a year ('000s) |
|---|---|---|---|---|
| US: GM HT soybeans | 210 | 93 | 1,070 | 475 |
| Argentina: GM HT soybeans | 736 | 327 | 11,186 | 4,972 |
| Brazil GM HT soybeans | 394 | 175 | 5,985 | 2,660 |
| Bolivia, Paraguay, Uruguay: GM HT soybeans | 156 | 69 | 2,365 | 1,051 |
| Canada: GM HT canola | 203 | 90 | 1,024 | 455 |
| US: GM HT corn | 210 | 93 | 2,983 | 1,326 |
| Global GM IR cotton | 45 | 20 | 0 | 0 |
| Brazil IR corn | 157 | 69 | 0 | 0 |
| *Total* | 2,111 | 936 | 24,613 | 10,939 |

*Notes*: Assumption: an average family car produces 150 g of carbon dioxide per km. A car does an average of 15,000 km/year and therefore produces 2,250 kg of carbon dioxide/year.

The additional soil carbon sequestration gains resulting from reduced tillage with GM crops accounted for a reduction of 24,613 million kg of $CO_2$ emissions in 2012. This is equivalent to removing nearly 10.9 million cars from the roads per year. In total, the carbon savings from reduced fuel use and soil carbon sequestration in 2012 were equal to removing 11.88 million cars from the road (equal to 41% of all registered cars in the United Kingdom).

## 1.6. CONCLUSIONS

Crop biotechnology 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 17.3 million adopting farmers who have applied the technology to 160 million hectares in 2012.

During the past 17 years, this technology has made important positive socioeconomic and environmental contributions. These have arisen even though only a limited range of GM agronomic traits have so far been commercialized, in a small range of crops.

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

The gains from the GM IR traits have mostly been delivered directly from the technology (yield improvements, reduced production risk and decreased use of insecticides). Thus, farmers (mostly in developing countries) have been able to both improve their productivity and economic returns, whilst also practicing more environment-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 soybeans) 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).

Both IR and HT traits have made important contributions to increasing world production levels of soybeans, corn, cotton, and canola.

In relation to GM HT crops, however, overreliance on the use of glyphosate by some farmers, in some regions, has contributed to the evolution and spread of HR weeds. As a result, farmers are increasingly adopting a mix of reactive and proactive weed management strategies incorporating a mix of herbicides. Despite this, the overall environmental and economic gain from the use of GM crops has been, and continues to be, substantial.

Overall, there is a considerable body of evidence, in the peer-reviewed literature, and summarized in this chapter, that quantifies the positive economic and environmental impacts of crop biotechnology. The analysis in this chapter therefore provides insights into the reasons why so many farmers around the world have adopted and continue to use the technology. Readers are encouraged to read the peer-reviewed papers cited, and the many others who have published on this subject (and listed in the references section of the two main papers from Brookes and Barfoot that provided the background information for this chapter) and to draw their own conclusions.

## LIFE BOX 1.1. NORMAN E. BORLAUG

**Norman E. Borlaug (1914–2009) Nobel Laureate, Nobel Peace Prize, 1970; Recipient of the Congressional Gold Medal, 2007.**

**Norman Borlaug.** Courtesy of 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 could he 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 3 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 8 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.

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 50 honorary doctorates from institutions in 18 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.; World Food Prize Laureate (2013); Winner of the Rank Prize for Nutrition (1987), and the Benjamin Franklin Medal in Life Sciences (2001); Member, National Academy of Sciences.**

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

**Mary-Dell Chilton** in the Washington University (St. Louis) greenhouse in 1982 with tobacco, the white rat of the plant kingdom. Courtesy of Mary-Dell Chilton.

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 worldwide 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 base pair 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 US 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.

## LIFE BOX 1.3. ROBERT T. FRALEY

**Robert Fraley, Chief Technology Officer, Monsanto Co.; World Food Prize Laureate (2013); National Academy of Science Award for the Industrial Application of Science (2008); National Medal of Technology from President Clinton (1998).**

**Robert T. Fraley.** Courtesy of Robert T. Fraley.

When I think back to my childhood on our family farm in central Illinois, I remember bailing hay and walking soybean fields to pull weeds. These pretty common farm jobs provided me with a perspective and the motivation to find better solutions to help farmers, like my dad, fight their most difficult problems. I am particularly grateful for my experience on our family farm because I learned firsthand both how challenging farming really is and how farmers continually adopt new and improved innovations.

It's humbling to remember life as a young farm boy, and then look at my career which progressed to pioneering research on gene transfer in plants and the development of Roundup Ready® soybeans and other biotech innovations. Although, from a very young age I knew I wanted to pursue a career in research, I had no idea then where science and innovation would take me, allowing me to travel the globe, interact with so many interesting people, in a career I truly enjoy.

Growing up in a rural setting, I attended a very small high school. In fact, I was the only student in my high school biology and physics classes. While a bit intimidated by how much one-on-one time I had with my science teacher, for me, this was an opportunity to grow, ask questions and absorb a new world of science and information. After graduating from high school, I received my Bachelor in Science at the University of Illinois, which established a sound foundation for my future. I continued my education at the U of I where I earned my Ph.D. in microbiology and biochemistry. I then spent 2 years of postdoctoral fellowship research at University of California, San Francisco, where I studied ways to introduce genes into plant and animal cells using liposomes. This was the period where I became focused on how biotechnology could be used to improve crops.

In 1981, Dr. Ernie Jaworski hired me to join a small, but talented team of scientists at Monsanto. It was exciting to work with this team. I valued our collaborative efforts to address some of agriculture's greatest challenges. Ironically though, our research started by using *Agrobacterium* to introduce new genes into the petunia, not your traditional crop! Looking back, this was a great decision because we were able to quickly prove the science. The petunia became the first genetically engineered plant, and it laid the foundation for many innovations in agriculture, including plants with resistance to pests, increased crop yields and protection against drought, and other environmental conditions.

As we advanced the research and technology, we developed solutions to help farmers address challenges on their farms. We shared our research results and safety analyses with the scientific community, regulatory bodies around the world and our farmer customers. Excitement supporting the science continued to spread and our team became recognized as key contributors to the worldwide scientific and agriculture communities. This was very humbling and led to an experience I will never forget, receiving the National Medal of Technology from President Clinton in 1998.

Looking back on all this though, we didn't do a great job of communicating directly with consumers and because of that, years later, we continue to work to address common misperceptions about how food is grown and if it is safe, nutritious, and sustainable. As a scientist, I was comfortable letting the evidence speak for itself. Although not joining the conversation with consumers earlier is my greatest regret, I am pleased that we have since engaged in this dialogue and continue to find common ground.

Throughout my career at Monsanto, I've held several roles within the Technology organization. My current role as Chief Technology Officer continues to excite me because I am not only leading a team of the top scientists in the ag industry, but I have the privilege of talking with farmers and seeing the process from beginning (in the lab) to end (on our customers' fields). One opportunity that has been especially rewarding for me in the last couple of years is engaging with broad audiences and furthering the dialogue with consumers, as well as partners like the Gates Foundation, Clinton Global Initiative and Conservation International. I see the opportunity to join the conversation with new and diverse groups as an important step in the right direction.

As I look back, the recognition that means the most to me as a scientist is the World Food Prize. The acknowledgment that biotechnology has made an important contribution to world food security was very rewarding and my close relationship with Dr. Norman Borlaug made this award even more special and personal. I have always admired Dr. Borlaug and the impact his scientific leadership provided. He emphasized the significance of food security and always impressed on me the need to think globally and forward for future generations. This is particularly critical today, as we face one of mankind's greatest challenges. By 2050, our global population will swell to 9.5 billion people, so we will need to produce more food in the next 30–35 years than we have in the entire history of the world. Dr. Borlaug said, "Food is the moral right of all who are born into this world," and by using agriculture effectively, we can address poverty, hunger, and overcome some of our biggest obstacles. Dr. Borlaug's leadership and mentorship continue to have a great impact on me, my career, and my world view.

The agriculture industry holds great growth potential and is at the center of so many of today's challenges—mitigating climate change, environmental impacts, growing population, changing diets, and food production demand. Continued innovation, both in biology and data science, can transform agriculture globally. I believe that we can not only meet the challenge of food security but also sustainably increase production to the point where we can reduce farming's footprint around the world. It is a very exciting time to be involved in agriculture and I encourage all who are interested in science to consider career opportunities in this industry. The innovation and developments that create sustainable solutions for farmers can lead to fulfilling and rewarding careers.



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