GM Crops & Food, 9:59–89, 2018
© 2018 Taylor & Francis
ISSN: 2164-5698 print /2164-5701 online
DOI: 10.1080/21645698.2018.1464866

ORIGINAL ARTICLES

Farm income and production impacts of using GM crop technology 1996–2016

Graham Brookes and Peter Barfoot

PG Economics Ltd, Dorchester, UK

ABSTRACT. This paper estimates the value of using genetically modified (GM) crop technology in agriculture at the farm level. It follows and updates earlier annual studies which examined impacts on yields, key variable costs of production, direct farm (gross) income and impacts on the production base of the four main crops of soybeans, corn, cotton and canola. The commercialisation of GM crops has occurred at a rapid rate since the mid 1990s, with important changes in both the overall level of adoption and impact occurring in 2016. This annual updated analysis shows that there continues to be very significant net economic benefits at the farm level amounting to $18.2 billion in 2016 and $186.1 billion for the period 1996–2016 (in nominal terms). These gains have been divided 48% to farmers in developed countries and 52% to farmers in developing countries. About 65% of the gains have derived from yield and production gains with the remaining 35% coming from cost savings. The technology has also made important contributions to increasing global production levels of the four main crops, having, for example, added 213 million tonnes and 405 million tonnes respectively, to the global production of soybeans and maize since the introduction of the technology in the mid 1990s.

KEYWORDS. yield, cost, income, production, genetically modified crops

INTRODUCTION

2016 represents the twenty first year of widespread cultivation of crops containing genetically modified (GM) traits, with our estimate of the global planted area of GM-traited crops in this year to be about 178 million hectares.

Correspondence to: Graham Brookes; PG Economics Ltd, Stafford House, 10 Prince of Wales Rd, Dorchester, Dorset, DT1 1PW, UK; E-mail: graham.brookes@btinternet.com

Received February 15, 2018; Accepted April 5, 2018.

BIOGRAPHICAL NOTES. Graham Brookes and Peter Barfoot are agricultural economists with PG Economics UK Ltd, specialists in assessing the impact of new technology in agriculture.

During this period, there have been many papers assessing the farm level economic and farm income impacts associated with the adoption of this technology. The authors of this paper have, since 2005, engaged in an annual exercise to aggregate and update the sum of these various studies, and where possible to supplement this with new analysis. The aim of this has been to provide an up to date and as accurate as possible assessment of some of the key farm level economic impacts associated with the global adoption of crops containing GM traits. It is also hoped the analysis continues to contribute to greater understanding of the impact of this technology and to facilitate more informed decision-making, especially in countries where crop biotechnology is currently not permitted.

This study updates the findings of earlier analysis into the global impact of GM crops since their commercial introduction in 1996 by integrating data and analysis for 2016. Previous analysis by the current authors has been published in various journals, with the last analysis being Brookes and Barfoot.[1] The methodology and analytical procedures in this present discussion are unchanged to allow a direct comparison of the new with earlier data. Readers should however, note that some data presented in this paper are not directly comparable with data presented in previous analysis because the current paper takes into account the availability of new data and analysis (including revisions to data for earlier years).

In order to save readers of this paper the chore of consulting the past papers for details of the methodology and arguments, these are included in full in this paper.

The analysis concentrates on gross farm income effects because these are a primary driver of adoption amongst farmers (both large commercial and small-scale subsistence). It also quantifies the (net) production impact of the technology. The authors recognise that an economic assessment could examine a broader range of potential impacts (eg, on labour usage, household incomes, local communities and economies).

However, these are not included because undertaking such an exercise would add considerably to the length of the paper and an assessment of wider economic impacts would probably merit a separate assessment in its own right.

RESULTS AND DISCUSSION

a) *Herbicide Tolerant (HT) Crops*

The main impact of GM HT (largely tolerant to the broad-spectrum herbicide glyphosate) technology has been to provide more cost effective (less expensive) and easier weed control for farmers. Nevertheless, some users of this technology have also derived higher yields from better weed control (relative to weed control obtained from conventional technology). The magnitude of these impacts varies by country and year, and is mainly due to prevailing costs of different herbicides used in GM HT systems versus conventional alternatives, the mix and amounts of herbicides applied, the cost farmers pay for accessing the GM HT technology and levels of weed problems. The following important factors affecting the level of cost savings achieved in recent years should be noted:

- The mix and amounts of herbicides used on GM HT crops and conventional crops are affected by price and availability of herbicides. Herbicides used include both ‘older’ products that are no longer protected by patents and newer ‘patent-protected’ chemistry, with availability affected by commerical decisions of suppliers to market or withdraw products from markets and regulation (eg, changes to approval processes). Prices also vary by year and country;
- The amount farmers pay for use of the technology varies by country. Pricing of technology (all forms of seed and crop protection technology, not just GM technology) varies according to the level of benefit that farmers are likely to derive from it. In addition, it is influenced by intellectual property rights (patent protection, plant breeders’ rights and rules relating to use of farm-saved seed). In

countries with weaker intellectual property rights, the cost of the technology tends to be lower than in countries where there are stronger rights. This is examined further in c) below;

- Where GM HT crops (tolerant to glyphosate) have been widely grown, some incidence of weed resistance to glyphosate has occurred and resistance has become a major concern in some regions. This has been attributed to how glyphosate was used; because of its broad-spectrum post-emergence activity, it was often used as the sole method of weed control. This approach to weed control put tremendous selection pressure on weeds and as a result contributed to the evolution of weed populations predominated by resistant individual weeds. It should, however, be noted that there are hundreds of resistant weed species confirmed in the International Survey of Herbicide Resistant Weeds (www.weedscience.com)[76]. Worldwide, there are 41 weed species that are currently resistant to glyphosate (accessed February 2018), compared to 160 weed species resistant to ALS herbicides (eg, chlorimuron ethyl commonly used in conventional soybean crops) and 74 weed species resistant to photosystem II inhibitor herbicides (eg, atriazine commonly used in corn production). In addition, GM HT technology has played a major role in facilitating the adoption of no and reduced tillage production techniques in North and South America. This has also probably contributed to the emergence of weeds resistant to herbicides like glyphosate and to weed shifts towards those weed species that are not well controlled by glyphosate. As a result, growers of GM HT crops are increasingly being advised to include other herbicides (with different and complementary modes of action) in combination with glyphosate in their weed management systems, even where instances of weed resistance to glyphosate have not been found. This change in weed management emphasis also reflects the broader agenda of developing strategies across all forms of cropping systems to minimise and slow down the potential for weeds developing resistance to existing technology solutions.[2] At the macro level, these changes have influenced the mix, total amount, cost and overall profile of herbicides applied to GM HT crops. Whilst this has resulted in the weed control costs associated with growing GM HT crops generally being higher in 2016 than 10–15 years previously, relative to the conventional alternative, GM HT crops have continued to offer important economic advantages for most users, either in the form of lower costs of production or higher yields (arising from better weed control). It should also be noted that many of the herbicides used in conventional production systems had significant resistance issues themselves in the mid 1990s and this was one of the reasons why glyphosate tolerant soybeans were rapidly adopted, as glyphosate provided good control of these weeds. If the GM HT technology was no longer delivering net economic benefits, it is likely that farmers around the world would have significantly reduced their adoption of this technology in favour of conventional alternatives. The fact that GM HT global crop adoption levels have not fallen in recent years suggests that farmers must be continuing to derive important economic benefits from using the technology.

These points are further illustrated in the analysis below.

GM HT soybeans

The impact of this technology on gross farm income is summarised in Table 1. The main farm level gain has arisen from a reduction in the cost of production, mainly through lower expenditure on weed control (mostly herbicides). Not surprisingly, where yield gains have occurred from improvements in the level of weed control, the average farm income gain has been higher, in countries such as Romania, Mexico and

TABLE 1. GM HT soybeans: Summary of average gross farm level income impacts 1996–2016 ($/hectare).

Country	Cost of technology	Average gross farm income benefit (after deduction of cost of technology)	Aggregate income benefit (million $)	Type of benefit	References
1st generation GM HT soybeans					
Romania (to 2006 only)	50–60	104	44.6	Small cost savings of about $9/ha, balance due to yield gains of +13% to +31%	Brookes[10] Monsanto Romania[11]
Argentina	2–4	22.5 plus second crop benefits of 216	18,567.3	Cost savings plus second crop gains	Qaim and Traxler[12] Trigo and CAP[13] and updated from 2008 to reflect herbicide usage and price changes
Brazil	7–25	32	7,220.2	Cost savings	Parana Department of Agriculture[14] Galveo[15–17] and updated to reflect herbicide usage and price changes
US	15–57	34	13,297.3	Cost savings	Marra et al[18] Carpenter and Gianessi[19] Sankala and Blumenthal[7,8] Johnson and Strom[20] And updated to reflect herbicide price and common product usage
Canada	20–40	21	200.6	Cost savings	George Morris Center[21] and updated to reflect herbicide price and common product usage
Paraguay	4–10	16.5 plus second crop benefits of 301	1,199.1	Cost savings	Based on Argentina as no country-specific analysis identified. Impacts confirmed by industry sources and herbicide costs and usage updated 2009 onwards from herbicide survey data AMIS Global/Kleffmann[22]

Uruguay	2–4	19	183.2	Cost savings	Based on Argentina as no country-specific analysis identified. Impacts confirmed by industry sources and herbicide costs and usage updated 2009 onwards from herbicide survey data AMIS Global/Kleffmann[22]
South Africa	2–30	9	38.4	Cost savings	As there are no published studies available, based on data from industry sources and herbicide costs and usage updated 2009 onwards from herbicide survey data AMIS Global/Kleffmann[22]
Mexico	20–47	40	6.1	Cost savings plus yield impacts in range of −2% to +13%	Monsanto annual monitoring reports submitted to Ministry of Agriculture and personal communications
Bolivia	3–4	97	775.6	Cost savings plus yield gain of +15%	Fernandez W et al[23]
2nd^{t} generation GM HT soybeans					
US and Canada	50–67	120 (US)	12,329.1 (US)	Cost savings as first generation plus yield gains in range of +5% to +11%	As first generation GM HT soybeans plus annual farm level survey data from Monsanto USA[3]
		110 (Can)	662.8 (Can)		
Intacta soybeans					
Brazil	33–56	113	4,207.4	Herbicide cost saving as 1st generation plus insecticide saving $19/ha and yield gain +9% to +10%	Monsanto Brazil pre commercial trials and post market (farm survey) monitoring, MB Agro[24]
Argentina	30–56	64	497.4	Herbicide cost saving as 1st generation plus insecticide saving $21/ha and yield gain +7% to +9%	Monsanto Argentina pre commercial trials and post market monitoring surveys

(Continued on next page)

TABLE 1. GM HT soybeans: Summary of average gross farm level income impacts 1996–2016 ($/hectare). *(Continued)*

Country	Cost of technology	Average gross farm income benefit (after deduction of cost of technology)	Aggregate income benefit (million $)	Type of benefit	References
Paraguay	30–56	122	437.1	Herbicide cost saving as 1st generation plus insecticide saving $33/ha and yield gain +9% to +13%	Monsanto Paraguay pre commercial trials and post market monitoring surveys
Uruguay	30–56	62	69.5	Herbicide cost saving as 1st generation plus insecticide saving $19/ha and yield gain +7% to +9%	Monsanto Uruguay pre commercial trials and post market monitoring surveys

Notes.

1.Romania stopped growing GM HT soybeans in 2007 after joining the European Union, where the trait is not approved for planting

2.The range in values for cost of technology relates to annual changes in the average cost paid by farmers. It varies for reasons such as the price of the technology set by seed companies, exchange rates, average seed rates and values identified in different studies

3.Intacta soybeans (HT and IR) first grown commercially in 2013

4.For additional details of how impacts have been estimated, see examples in Appendix 1

5.AMIS Global/Kleffmann are subscription-based data sources (derived from farmer surveys) on pesticide use

6.References to Monsanto Argentina, Brazil, Paraguay and Uruguay as sources of data from pre-commericalisation trials and post market monitoring – this is unpublished data provided to the authors by these companies on a yearly basis covering seed premium, yield comparisons and cost of insecticide/number of insecticide treatment comparisons for Intacta crops versus conventional and GM HT (only) crops. The data derives from survey-based monitoring of sites growing each crop

Bolivia. A second generation of GM HT soybeans became available to commercial soybean growers in the US and Canada in 2009. This technology offered the same tolerance to glyphosate as the first generation (and the same cost saving) but with higher yielding potential. The realisation of this potential is shown in the higher average gross farm income benefits (Table 1). GM HT soybeans have also facilitated the adoption of no tillage production systems, shortening the production cycle. This advantage has enabled many farmers in South America to plant a crop of soybeans immediately after a wheat crop in the same growing season. The second crop, additional to traditional 'one crop' soybean production, has added considerably to farm incomes and to the volumes of soybean production in countries such as Argentina and Paraguay.

Overall, in 2016, GM HT technology in soybeans (excluding second generation 'Intacta' soybeans: see below) has boosted gross farm incomes by $4.37 billion, and since 1996 has delivered $54.6 billion of extra farm income. Of the total cumulative farm income gains from using GM HT soybeans, $24.6 billion (45%) has been due to yield gains/second crop benefits and the balance, 55%, has been due to cost savings.

GM HT and IR (intacta) soybeans

This combination of GM herbicide tolerance (to glyphosate) and insect resistance in soybeans was first grown commercially in 2013, in South America. In the first four years, the technology was used on approximately 49.6 million hectares and contributed an additional $5.2 billion to gross farm income of soybean farmers in Argentina, Brazil, Paraguay and Uruguay, through a combination of cost savings (decreased expenditure on herbicides and insecticides) and higher yields (see Table 1).

GM HT maize

The adoption of GM HT maize has mainly resulted in lower costs of production, although yield gains from improved weed control have arisen in Argentina, Brazil, the Philippines and Vietnam (Table 2).

In 2016, the total global farm income gain from using this technology was $2.1 billion with the cumulative gain over the period 1996–2016 being $13.1 billion. Within this, $4.5 billion (34%) was due to yield gains and the rest derived from lower costs of production.

GM HT cotton

The use of GM HT cotton delivered a gross farm income gain of about $130.1 million in 2016. In the 1996–2016 period, the total gross farm income benefit was $1.92 billion. As with other GM HT traits, these farm income gains have mainly arisen from cost savings (71% of the total gains), although there have been some yield gains in Argentina, Brazil, Mexico and Colombia (Table 3).

Other HT crops

GM HT canola (tolerant to glyphosate or glufosinate) has been grown in Canada, the US, and more recently Australia, whilst GM HT sugar beet is grown in the US and Canada. The gross farm income impacts associated with the adoption of these technologies are summarised in Table 4. In both cases, the main farm income benefit has derived from yield gains. In 2016, the total global income gain from the adoption of GM HT technology in canola and sugar beet was $559 million and cumulatively since 1996, it was $6.44 billion.

b) Insect Resistant (GM IR) Crops

The main way in which these technologies have impacted on farm incomes has been through lowering the levels of pest damage and hence delivering higher yields (Table 5).

The greatest improvement in yields has occurred in developing countries, where conventional methods of pest control have been least effective (eg, reasons such as poorly developed extension and advisory services, lack of access to finance to fund use of crop protection application equipment and

TABLE 2. GM HT maize: Summary of average gross farm income impacts 1996–2016 ($/hectare).

Country	Cost of technology	Average gross farm income benefit (after deduction of cost of technology)	Aggregate income benefit (million $)	Type of benefit	References
US	15–30	28	8,450.0	Cost savings	Carpenter and Gianessi[19] Sankala and Blumenthal[7,8] Johnson and Strom[20] Also updated annually to reflect herbicide price and common product usage
Canada	17–35	15	185.3	Cost savings	Monsanto Canada (personal communications) and updated annually since 2008 to reflect changes in herbicide prices and usage
Argentina	16–33	108	2,391.9	Cost savings plus yield gains over 10% and higher in some regions	Personal communication from Monsanto Argentina, Grupo CEO and updated since 2008 to reflect changes in herbicide prices and usage
South Africa	9–18	5	65.2	Cost savings	Personal communication from Monsanto South Africa and updated since 2008 to reflect changes in herbicide prices and usage
Brazil	10–32	38	1,831.9	Cost savings plus yield gains of +1% to +7%	Galveo[15–17]
Colombia	14–24	15	6.0	Cost savings	Mendez et al[25]
Philippines	24–47	31	171.0	Cost savings plus yield gains of +5% to +15%	Gonsales[26] Monsanto Philippines (personal communications) Updated since 2010 to reflect changes in herbicide prices and usage
Paraguay	13–17	3	4.1	Cost saving	Personal communication from Monsanto Paraguay and AMIS Global/Kleffman – annually updated to reflect changes in herbicide prices and usage

Uruguay	6–17	3	1.36	Cost saving	Personal communication from Monsanto Uruguay and AMIS Global/Kleffman – updated annually to reflect changes in herbicide prices and usage
Vietnam	26–28	37	1.43		Brookes[27]

1. The range in values for cost of technology relates to annual changes in the average cost paid by farmers. It varies for reasons such as the price of the technology set by seed companies, exchange rates, average seed rates and values identified in different studies

2. For additional details of how impacts have been estimated, see examples in Appendix 1

3. AMIS Global/Kleffmann are subscription-based data sources (derived from farmer surveys) on pesticide use

4. References to Monsanto Argentina, Canada, South Africa, Philippines, Paraguay and Uruguay as sources of data – this is unpublished data provided to the authors by these companies on a yearly basis covering seed premium and typical herbicide treatments used on GM HT and conventional crops

5. Reference to changes in herbicide prices and usage – author estimates drawing on AMIS Global/Kleffmann data and other similar database sources eg, Kynetec (for the US) and extension services (eg, Ontario Ministry of Agriculture in Canada)

TABLE 3. GM HT cotton summary of average gross farm income impacts 1996–2016 ($/hectare).

Country	Cost of technology	Average gross farm income benefit (after deduction of cost of technology)	Aggregate income benefit (million $)	Type of benefit	References
US	13–82	20	1,135.5	Cost savings	Carpenter and Gianessi[19] Sankala and Blumenthal[7,8] Johnson and Strom[20] Also updated to reflect herbicide price and common product usage
South Africa	13–32	33	4.8	Cost savings	Personal communication from Monsanto South Africa and updated since 2008 to reflect changes in herbicide prices and usage
Australia	32–82	28	113.2	Cost savings	Doyle et al[28] Monsanto Australia (personal communications) and updated to reflect changes in herbicide usage and prices
Argentina	10–30	43	183.9	Cost savings and yield gain of +9%	Personal communication from Monsanto Argentina, Grupo CEO and updated since 2008 to reflect changes in herbicide prices and usage
Brazil	26–54	62	180.3	Cost savings plus yield gains of +1.6% to +4%	Galveo[15–17]
Mexico	29–79	267	274.4	Cost savings plus yield gains of +3% to +20%	Monsanto Mexico annual monitoring reports submitted to the Ministry of Agriculture and personal communications
Colombia	96–187	95	24.8	Cost savings plus yield gains of +4%	Monsanto Colombia annual personal communications

1. The range in values for cost of technology relates to annual changes in the average cost paid by farmers. It varies for reasons such as the price of the technology set by seed companies, exchange rates, average seed rates, the nature and effectiveness of the technology (eg, second generation 'Flex' cotton offered more flexible and cost-effective weed control than the earlier first generation of HT technology) and values identified in different studies

2. For additional details of how impacts have been estimated, see examples in Appendix 1

3. References to Monsanto Argentina, Australia, South Africa and Colombia as sources of data – this is unpublished data provided to the authors by these companies on a yearly basis covering seed premium and typical herbicide treatments used on GM HT and conventional crops

4. Reference to Monsanto Mexico annual monitoring reports. These are unpublished, annual monitoring of crop reports that the company is required to submit to the Mexican Ministry of Agriculture, as part of post market monitoring requirements. This provides data on seed premia, cost of weed control and production and yields for GM HT cotton versus conventional to a regional level

5. Reference to changes in herbicide prices and usage – author estimates drawing on AMIS Global/Kleffmann data and other similar database sources eg, Kynetec (for the US) and extension services (eg, New South Wales Department of Agriculture in Australia)

TABLE 4. Other GM HT crops summary of average gross farm income impacts 1996–2016 ($/hectare).

Country	Cost of technology	Average farm income benefit (after deduction of cost of technology)	Aggregate income benefit (million $)	Type of benefit	References
GM HT canola					
US	12–33	49	360.9	Mostly yield gains of +1% to +12% (especially Invigor canola)	Sankala and Blumenthal[7],[8] Johnson and Strom[20] And updated to reflect herbicide price and common product usage
Canada	12–32	57	5,520.0	Mostly yield gains of +3% to +12% (especially Invigor canola)	Canola Council[29] Gusta et al[30] and updated to reflect herbicide price changes and seed variety trial data (on yields)
Australia	10–41	45	89.9	Mostly yield gains of +12% to +22% (where replacing triazine tolerant canola) but no yield gain relative to other non GM (herbicide tolerant canola)	Monsanto Australia,[31] Fischler and Tozer[32] and Hudson and Richards[33]
GM HT sugar beet					
US and Canada	130–151	116	454.0	Mostly yield gains of +3% to +13%	Kniss[34] Khan[35] Jon-Joseph et al[36] Annual updates of herbicide price and usage data

Notes.

1. In Australia, one of the most popular type of production has been canola tolerant to the triazine group of herbicides (tolerance derived from non GM techniques). It is relative to this form of canola that the main farm income benefits of GM HT (to glyphosate) canola has occurred
2. InVigor' hybrid vigour canola (tolerant to the herbicide glufosinate) is higher yielding than conventional or other GM HT canola and derives this additional vigour from GM techniques
3. The range in values for cost of technology relates to annual changes in the average cost paid by farmers. It varies for reasons such as the price of the technology set by seed companies, exchange rates, average seed rates and values identified in different studies
4. For additional details of how impacts have been estimated, see examples in Appendix 1
5. References to Monsanto Australia as a source of data – this is unpublished data provided to the authors by this company on a yearly basis covering seed premium and typical herbicide treatments used on GM HT and conventional crops
6. Reference to changes in herbicide prices and usage – author estimates drawing on AMIS Global/Kleffmann data and other similar database sources eg, Kynetec (for the US)

TABLE 5. Average (%) yield gains GM IR cotton and maize 1996–2016.

	Maize insect resistance to corn boring pests	Maize insect resistance to rootworm pests	Cotton insect resistance	References
US	7.0	5.0	9.9	Carpenter and Gianessi[19] Marra et al[18] Sankala and Blumenthal[7,8] Hutchison et al[37] Rice[38] Mullins and Hudson[9]
China	N/a	N/a	10.0	Pray et al[39]
South Africa	11.1	N/a	24.0	Gouse et al[40-42] Van der Wald[43] Ismael et al[44] Kirsten et al[45] James[46]
Honduras	23.8	N/a	N/a	Falk Zepeda et al[47,48]
Mexico	N/a	N/a	11.0	Traxler and Godoy-Avila[75] Monsanto Mexico annual cotton monitoring reports
Argentina	6.0	N/a	30.0	Trigo[49] Trigo and Cap[13] Qaim and De Janvry[50,51] Elena[52]
Philippines	18.2	N/a	N/a	Gonsales[53] Gonsales et al[26] Yorobe[54] Ramon[55]
Spain	11.2	N/a	N/a	Brookes[56,57] Gomez-Barbero, Barbel M A and Rodriguez-Corejo[58] Riesgo et al[59]
Uruguay	5.6	N/a	N/a	As Argentina (no country-specific studies available and industry sources estimate similar impacts as in Argentina)
India	N/a	N/a	30.0	Bennett et al[4] IMRB[5,6] Herring and Rao[60]
Colombia	21.8	N/a	18.0	Mendez et al[25] Zambrano et al[61]
Canada	7.0	5.0	N/a	As US (no country-specific studies available and industry sources estimate similar impacts as in the US)
Burkina Faso	N/a	N/a	18.0	Vitale J et al,[62] Vitale J[63]
Brazil	11.8	N/a	1.3	Galveo[15–17,64] Monsanto Brazil[65]
Pakistan	N/a	N/a	21.0	Nazli et al,[66] Kouser and Qaim[67,68]
Myanmar	N/a	N/a	30.7	USDA[69]
Australia	N/a	N/a	Nil	Doyle[70] James[71] CSIRO[72] Fitt[73]

(Continued on next page)

TABLE 5. Average (%) yield gains GM IR cotton and maize 1996–2016. *(Continued)*

	Maize insect resistance to corn boring pests	Maize insect resistance to rootworm pests	Cotton insect resistance	References
Paraguay	5.5	N/a	Not available	As Argentina (no country-specific studies available and industry sources estimate similar impacts as in Argentina)
Vietnam	7.2	N/a	N/a	Brookes[27]

Notes.

1. N/a = not applicable

2. Reference to Monsanto Mexico annual monitoring reports. These are unpublished, annual monitoring of crop reports that the company is required to submit to the Mexican Ministry of Agriculture, as part of post market monitoring requirements. This provides data on seed premia, cost of pest control and production and yields for GM IR cotton versus conventional to a regional level

6. GM IR maize performance in Uruguay and Paraguay. Industry sources consulted for using Argentina impact data as a suitable proxy for impact in these countries include Monsanto Argentina, Uruguay and Paraguay, Argenbio (Argentine Biotechnology Association) and Trigo E (Grupo CEO)

products), with any cost savings associated with reduced insecticide use being mostly found in developed countries. These effects can be seen in the level of farm income gains that have arisen from the adoption of these technologies, as shown in Table 6.

At the aggregate level, the global gross farm income gains from using GM IR maize and cotton in 2016 were \$4.81 billion and \$3.7 billion respectively. Cumulatively since 1996, the gains have been \$50.6 billion for GM IR maize and \$54 billion for GM IR cotton.

c) *GM Drought Tolerant Maize*

Drought tolerant maize has been grown in parts of the US since 2014 and in 2016 was planted on 1.34 million hectares. Drawing on yield comparison data with other drought tolerant maize (varieties conveying drought tolerance that is not derived from GM technology) from field trials (source: Monsanto US[3] Field Trials Network in the Western Great Plains), this suggests that the technology is providing users with a net yield gain of about 2.3% and a small cost saving in irrigation costs. After taking into consideration, the additional cost of the seed compared to non-GM drought tolerant maize), the average gross farm income gain (2014–2016) has been about \$15/ha. In 2016, this resulted to an aggregate farm income gain of about \$20 million and over the period 2014–2016, a total gain of about \$33.3 million.

d) *Aggregated (Global Level) Impacts*

GM crop technology has had a significant positive impact on global gross farm income, which amounted to \$18.2 billion in 2016. This is equivalent to having added 5.4% to the value of global production of the four main crops of soybeans, maize, canola and cotton. Since 1996, gross farm incomes have increased by \$186.1 billion.

At the country level, US farmers have been the largest beneficiaries of higher incomes, realising over \$80.3 billion in extra income between 1996 and 2016. This is not surprising given that US farmers were first to make widespread use of GM crop technology and for many years the GM adoption levels in all four US crops have been in excess of 80%. Important farm income benefits (\$46.4 billion) have occurred in South America (Argentina, Bolivia, Brazil, Colombia, Paraguay and Uruguay), mostly from GM technology in soybeans and maize. GM IR cotton has also been responsible for an additional \$40.8 billion additional income for cotton farmers in China and India.

In 2016, 55% of the farm income benefits were earned by farmers in developing countries. The vast majority of these gains have been from GM IR cotton and GM HT soybeans. Over the twenty-one years 1996–2016, the cumulative farm income gain derived by developing country farmers was \$96 billion, equal to 51.7% of the total farm income during this period.

The cost to farmers for accessing GM technology, across the four main crops, in 2016,

TABLE 6. GM IR crops: Average gross farm income benefit 1996–2016 ($/hectare).

Country	GM IR maize: cost of technology	GM IR maize (income benefit after deduction of cost of technology)	Aggregate income benefit GM IR maize (million $)	GM IR cotton: cost of technology	GM IR cotton (income benefit after deduction of cost of technology)	Aggregate income benefit GM IR cotton (million $)
US	17–32 IRCB, 22–42 IR CRW	81 IRCB, 77 IR CRW	38,509.0	26–58	111	5,430.5
Canada	17–26 IRCB, 22–42 IR CRW	75 IRCB 87 IR CRW	1,457.6	N/a	N/a	N/a
Argentina	10–33	28	1,108.8	21–86	240	921.0
Philippines	30–47	100	553.0	N/a	N/a	N/a
South Africa	9–17	95	2,173.2	14–50	152	34.5
Spain	17–51	207	274.9	N/a	N/a	N/a
Uruguay	11–33	30	29.6	N/a	N/a	N/a
Honduras	100	48	11.5	N/a	N/a	N/a
Colombia	30–49	275	130.0	50–175	68	21.1
Brazil	44–69	74	6,222.9	26–52	40	134.9
China	N/a	N/a	N/a	38–60	349	19,644.9
Australia	N/a	N/a	N/a	85–299	211	953.7
Mexico	N/a	N/a	N/a	48–75	215	272.1
India	N/a	N/a	N/a	12–54	207	21,121.7
Burkina Faso	N/a	N/a	N/a	51–54	97	204.6
Myanmar	N/a	N/a	N/a	17–20	160	358.4
Pakistan	N/a	N/a	N/a	4–15	235	4,794.3
Paraguay	16–20	19	32.0	N/a	N/a	N/a
Vietnam	38–42	105	4.0		N/a	
Average across all user countries		**76**			**219**	

Notes.

1. GM IR maize all are IRCB unless stated (IRCB = insect resistance to corn boring pests), IRCRW = insect resistance to corn rootworm
2. The range in values for cost of technology relates to annual changes in the average cost paid by farmers. It varies for reasons such as the price of the technology set by seed companies, the nature and effectiveness of the technology (eg, second generation ‘Bollgard’ cotton offered protection against a wider range of pests than the earlier first generation of ‘Bollgard’ technology), exchange rates, average seed rates and values identified in different studies.
3. Average across all countries is a weighted average based on areas planted in each user country
4. n/a = not applicable
5. Sources – as Table 5

was equal to 29% of the total value of technology gains. This is defined as the farm income gains referred to above plus the cost of the technology payable to the seed supply chain. Readers should note that the cost of the technology accrues to the seed supply chain including sellers of seed to farmers, seed multipliers, plant breeders, distributors and the GM technology providers.

In developing countries, the total cost was equal to 20% of total technology gains compared with 36% in developed countries. Whilst circumstances vary between countries, the higher share of total technology gains accounted for by farm income in developing countries relative to developed countries reflects factors such as weaker provision and enforcement of intellectual property rights in developing countries and the higher average level of farm income gain per hectare derived by farmers in developing countries compared to those in developed countries.

Sixty-five per cent of the total income gain over the 21-year period derives from higher yields and second crop soybean gains with 35% from lower costs (mostly on insecticides and herbicides). In terms of the two main trait types, insect resistance and herbicide tolerance have accounted for 52% and 48% respectively of the total income gain. The balance of the income gain arising from yield/production gains relative to cost savings is changing as second-generation GM crops are increasingly adopted. Thus in 2016 the split of total income gain came 72% from yield/production gains and 28% from cost savings.

Crop production effects

Based on the yield impacts used in the direct farm income benefit calculations above 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 7).

The GM IR traits, used in maize and cotton, have accounted for 93.5% of the additional maize production and 98.9% 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 where the levels of *Heliothis sp* (boll and bud worm pests) pest control previously obtained with intensive insecticide use were very good. The main benefit and reason for adoption of this technology in Australia has arisen from significant cost savings and the associated environmental gains from reduced insecticide use, when compared to average yields derived from crops using conventional technology (such as application of insecticides and seed treatments). The average yield impact across the total area planted to these traits over the 21 years since 1996 has been +14% for maize and +15% for cotton.

TABLE 7. Additional crop production arising from positive yield effects of GM crops.

	1996–2016 additional production (million tonnes)	2016 additional production (million tonnes)
Soybeans	213.47	31.56
Maize	404.91	47.36
Cotton	27.47	2.27
Canola	11.65	1.00
Sugar beet	1.2	0.17

Note: Sugar beet, US and Canada only (from 2008)

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 systems, 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 166.8 million tonnes to soybean production in Argentina and Paraguay between 1996 and 2016 (accounting for 83.4% of the total GM HT-related additional soybean production). Intacta soybeans added a further 13.46 million tonnes since 2013.

CONCLUDING COMMENTS

In the last 21 years, crop biotechnology has helped farmers grow more food using fewer resources by reducing the damage caused by pests and better controlling weeds. The highest yield increases have occurred in developing countries and this has contributed to a more reliable and secure food supply base in these countries. In South America, HT technology has helped farmers reduce tillage, shortening the time between planting and harvesting, allowing them the opportunity to grow an additional soybean crop after wheat in the same growing season.

With higher yields and less time and money spent managing pests and weeds, farmers have earned higher incomes. This has proved to be especially valuable for farmers in developing countries where, in 2016, an average $5 was received for each extra dollar invested in biotech crop seeds.

The widespread use of GM crop technology is also changing agriculture's land footprint by allowing farmers to grow more without needing to use additional land. To maintain global production levels at 2016 levels, without biotech crops, would have required farmers to plant an additional 10.8 million hectares (ha) of soybeans, 8.2 million ha of maize, 2.9 million ha of cotton and 0.5 million ha of canola, an area equivalent to the combined land area of Bangladesh and Sri Lanka.

Nevertheless, in relation to the use of HT crops, over reliance on the use of glyphosate and the lack of crop and herbicide rotation by farmers, in some regions, has contributed to the development of weed resistance. In order to address this problem and maintain good levels of weed control, farmers have increasingly adopted more integrated weed management strategies incorporating a mix of herbicides, other HT crops and cultural weed control measures (in other words using other herbicides with glyphosate rather than solely relying on glyphosate, using HT crops which are tolerant to other herbicides, such as glufosinate and using cultural practices such as mulching). This has added cost to the GM HT production systems compared to about 10–15 years ago, although relative to the current conventional alternative, the GM HT technology continues to offer important economic benefits in 2016.

Overall, there continues to be a considerable and growing body of evidence, in peer reviewed literature, and summarised in this paper, that quantifies the positive economic impacts of crop biotechnology. The analysis 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 below) and to draw their own conclusions.

METHODOLOGY

The report is based on detailed analysis of existing farm level impact data for GM crops, much of which can be found in peer reviewed literature. Most of this literature broadly refers to itself as 'economic impact' literature and applies farm accounting or partial budget approaches to assess the impact of GM crop technology on revenue, key costs of production (notably cost of seed, weed control, pest control and use of labour) and gross farm income. Whilst primary data for impacts of commercial cultivation were not available for every crop, in every year and for each country, a substantial body of representative research and analysis is available and this has been used as the basis for the analysis presented. The authors have also undertaken their own analysis of the impact of some trait-crop combinations in some countries (notably GM herbicide tolerant (HT) traits in North and South America) based on key input (eg, herbicide and insecticide usage) and cost data.

The farm level economic impact of the technology varies widely, both between and within regions/countries. Therefore, the analysis is considered on a case by case basis, using average performance and impact recorded in different crop and trait combinations by the studies reviewed. Where more than one piece of relevant research (eg, on the impact of using a GM trait on the yield of a crop in one country in a particular year) has been identified, the findings used in this analysis reflect the authors assessment of which research is most likely to be reasonably representative of impact in the country in that year. For example, there are many papers on the impact of GM insect resistant (IR) cotton in India. Few of these are reasonably representative of cotton growing across the country, with many papers based on small scale, local and unrepresentative samples of cotton farmers. Only the reasonably representative research has been drawn on for use in this paper – readers should consult the references to this paper to identify the sources used.

This approach may still both, overstate, or understate, the impact of GM technology for some trait, crop and country combinations, especially in cases where the technology has provided yield enhancements. However, as impact data for every trait, crop, location and year data is not available, the authors have had to extrapolate available impact data from identified studies to years for which no data are available. In addition, if the only studies available took place several years ago, there is a risk that basing current assessments on such comparisons may not adequately reflect the nature of currently available alternative (non-GM seed or crop protection) technology. The authors acknowledge that these factors represent potential methodological weaknesses. To reduce the possibilities of over/understating impact due to these factors, the analysis:

- Directly applies impacts identified from the literature to the years that have been studied. As a result, the impacts used vary in many cases according to the findings of literature covering different years. Examples where such data is available include the impact of GM insect resistant (IR) cotton: in India (see Bennett R et al,[4] IMRB[5] and IMRB[6]), in Mexico (see Traxler and Godoy-Avila[75] and Monsanto Mexico annual monitoring reports submitted to the Ministry of Agriculture in Mexico) and in the US (see Sankala & Blumenthal[7,8] Mullins & Hudson[9]). Hence, the analysis takes into account variation in the impact of the technology on yield according to its effectiveness in dealing with (annual) fluctuations in pest and weed infestation levels;
- Uses current farm level crop prices and bases any yield impacts on (adjusted – see below) current average yields. This introduces a degree of dynamic analysis that would, otherwise, be missing if constant prices and average yields identified in year-specific studies had been used;
- It includes some changes and updates to the impact assumptions identified in the literature based on new papers, annual consultation with local sources (analysts, industry representatives, databases of crop protection usage and prices) and some 'own analysis' of changes in crop protection usage and prices and of seed varieties planted;
- Adjusts downwards the average base yield (in cases where GM technology has been identified as having delivered yield improvements) on which the yield enhancement has been applied. In this way, the impact on total production is not overstated.

Detailed examples of how the methodology has been applied to calculate the 2016 impacts are presented in Appendix 1.

Other aspects of the methodology used to estimate the impact on direct farm income are as follows:

- Where stacked traits have been used, the individual trait components were analysed separately to ensure estimates of all traits were calculated. This is possible because the non-stacked seed has been (and in many cases continues to be) available and used by farmers and there are studies that have assessed trait-specific impacts;
- All values presented are nominal for the year shown and the base currency used is the US dollar. All financial impacts in other currencies have been converted to US dollars at prevailing annual average exchange rates for each year (source: United States Department of Agriculture Economics Research Service);
- The analysis focuses on changes in farm income in each year arising from impact of GM technology on yields, key costs of production (notably seed cost and crop protection expenditure but also impact on costs such as fuel and labour. Inclusion of these costs is, however, more limited than the impacts on seed and crop protection costs because only a few of the papers reviewed have included consideration of such costs in their analysis. In most cases the analysis relates to impact of crop protection and seed cost only, crop quality (eg, improvements in quality arising from less pest damage or lower levels of weed impurities which result in price premia being obtained from buyers) and the scope for facilitating the planting of a second crop in a season (eg, second crop soybeans in Argentina following wheat that would, in the absence of the GM HT seed, probably not have been planted). Thus, the farm income effect measured is essentially a gross margin impact (impact on gross

revenue less variable costs of production) rather than a full net cost of production assessment. Through the inclusion of yield impacts and the application of actual (average) farm prices for each year, the analysis also indirectly takes into account the possible impact of GM crop adoption on global crop supply and world prices.

The paper also includes estimates of the production impacts of GM technology at the crop level. These have been aggregated to provide the reader with a global perspective of the broader production impact of the technology. These impacts derive from the yield impacts and the facilitation of additional cropping within a season (notably in relation to soybeans in South America). Details of how these values were calculateed (for 2016) are shown in Appendix 1.

ACKNOWLEDGEMENT

The authors acknowledge that funding towards the researching of this paper was provided by Monsanto. The material presented in this paper is, however, the independent views of the authors – it is a standard condition for all work undertaken by PG Economics that all reports are independently and objectively compiled without influence from funding sponsors.

FUNDING

Monsanto Company

REFERENCES

1. Brookes G, Barfoot P. Farm income and production impacts of using GM crop technology 1996–2016. GM Crops. 2017;8(3):156–93. doi:10.1080/21645698.2017.1317919.
2. Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, et al. Reducing the risk of herbicide resistance: best management practices and recommendations. Weed Sci. 2012, Herbicide Resistant Weeds Special Issue, 60:31–62. doi:10.1614/WS-D-11-00155.1.
3. Monsanto US. Field trials network in the Western Great Plains. https://monsanto.com/products/learning-centers/gothenburg-learning-center/.
4. Bennett R, Ismael Y, Kambhampati U, Morse S. Economic impacts of GM cotton in India. AgBioforum. 2004;7(3):96–100.
5. IMRB. Socio-economic benefits of Bollgard and product satisfaction (in India). Mumbai, India: IMRB International; 2006.
6. IMRB. Socio-economic benefits of Bollgard and product satisfaction (in India). Mumbai, India: IMRB International; 2007.
7. Sankala S, Blumenthal E. Impacts on US agriculture of biotechnology-derived crops planted in 2003- an update of eleven case studies. NCFAP, Washington. 2003. www.ncfap.org.
8. Sankala S, Blumenthal E. Impacts on US agriculture of biotechnology-derived crops planted in 2005- an update of eleven case studies. 2005. NCFAP, Washington. www.ncfap.org.
9. Mullins W, Hudson J. Bollgard II versus Bollgard sister line economic comparisons. 2004 Beltwide cotton conferences, San Antonio, USA; Jan 2004.
10. Brookes G. The farm level impact of using Roundup Ready soybeans in Romania. Agbioforum. 2005;8(4):235–41. www.agbioforum.org.
11. Monsanto Romania. Unpublished results of farmer survey amongst soybean growers in 2006 – published in 2007.
12. Qaim M, Traxler G. Roundup Ready soybeans in Argentina: farm level & aggregate welfare effects. Agric Econ. 2005;32(1):73–86. doi:10.1111/j.0169-5150.2005.00006.x.
13. Trigo E, Cap E. Ten years of GM crops in Argentine Agriculture, ArgenBio. 2006. http://argenbio.org/biblioteca/Ten_Years_of_GM_Crops_in_Argentine_Agriculture_02_01_07.pdf.
14. Parana Department of Agriculture. Cost of production comparison: biotech and conventional soybeans, in USDA GAIN report, 2004. BR4629 of 11 November 2004. www.fas.usad.gov/gainfiles/200411/146118108.pdf.
15. Galveo A. Farm survey findings of impact of insect resistant corn and herbicide tolerant soybeans in Brazil, 2010, Celeres, Brazil. www.celeres.co.br.
16. Galveo A. Farm survey findings of impact of GM crops in Brazil, 2012, Celeres, Brazil. www.celeres.co.br.
17. Galveo A. Farm survey findings of impact of GM crops in Brazil, 2015, Celeres, Brazil. www.celeres.co.br.
18. Marra M, Pardey P, Alston J. The pay-offs of agricultural biotechnology: an assessment of the evidence, 2002, International Food Policy Research Institute, Washington, USA.
19. Carpenter J, Gianessi L. Agricultural Biotechnology: updated benefit estimates. Washington, USA:

National Centre for Food and Agricultural Policy (NCFAP); 2002.

20. Johnson S, Strom S. Quantification of the impacts on US agriculture of biotechnology-derived crops planted in 2006, 2008. NCFAP, Washington. www.ncfap.org.
21. George Morris Centre. Economic & environmental impacts of the commercial cultivation of glyphosate tolerant soybeans in Ontario. 2004, unpublished report for Monsanto Canada.
22. AMIS Global/Kleffmann. Subscription-based data sources (derived from farmer surveys) on pesticide use. Kleffmann Gmbh, Ludinghausen, Germany. www.kleffmann.com.
23. Fernandez W, Paz R, Zambrano P, Zepeda JF. GM soybeans in Bolivia. 2009, paper presented to the 13th ICABR conference, Ravello, Italy, June 2009.
24. MB Agro. Intacta soybeans: An economic view of the benefits of adopting the new technology. 2014 report commissioned by Monsanto Brazil.
25. Mendez K, Chaparro Giraldo A, Reyes Moreno G, Silva Castro C. Production cost analysis and use of pesticides in the transgenic and conventional crop in the valley of San Juan (Colombia). GM Crops. 2011;2(3):June-Dec 2011:163–8. doi:10.4161/gmcr.2.3.17591. PMID:22008311.
26. Gonsales L. Modern Biotechnology and Agriculture: a history of the commercialisation of biotechnology maize in the Philippines. Los Banos, Philippines: Strive Foundation; 2009. ISBN:978-971-91904-8-6.
27. Brookes G. The potential socio-economic and environmental impacts from adoption of corn hybrids with biotech trait/technologies in Vietnam. 2017. PG Economics, UK. www.pgeconomics.co.uk.
28. Doyle B. The Performance of Roundup Ready cotton 2001–2002 in the Australian cotton sector. Armidale, Australia: University of New England; 2003.
29. Canola Council of Canada. An agronomic & economic assessment of transgenic canola. 2001, Canola Council, Canada. www.canola-council.org.
30. Gusta M, Smyth S, Belcher K, Phillips P, Castle D. Economic benefits of GM HT canola for producers. AgBioForum. 2011;14(1):1–12.
31. Monsanto Australia. Survey of herbicide tolerant canola licence holders 2008.
32. Fischer J, Tozer P. Evaluation of the environmental and economic impact of Roundup Ready canola in the Western Australian crop production system, 2009. Curtin University of Technology Technical Report 11/2009.
33. Hudson D, Richards R. Evaluation of agronomic, environmental, economic and co-existence impacts following the introduction of GM canola in Australia 2010–2012. Agbioforum. 2014;17(1):1–12.
34. Kniss A. Comparison of conventional and glyphosate resistant sugarbeet the year of commercial introduction in Wyoming. J Sugar Beet Res. 2010;47:127–34. doi:10.5274/jsbr.47.3.127.
35. Khan M. Roundup Ready sugar beet in America. Br Sugar Beet Rev Winter. 2008;76(4):16–9.
36. Jon-Joseph AQ, Sprague CL. Weed management in wide-and narrow-row glyphosate resistant sugar beet. Weed Technol. 2010;24:523–8. doi:10.1614/WT-D-10-00033.1.
37. Hutchison W, Burkness EC, Mitchel PD, Moon RD, Leslie TW, Fleicher SJ, Abrahamson M, Hamilton KL, Steffey KL, Gray ME, et al. Area-wide suppression of European Corn Borer with Bt maize reaps savings to non-bt maize growers. Science. 2010;330:222–5. www.sciencemag.org. doi:10.1126/science.1190242. PMID:20929774.
38. Rice M. Transgenic rootworm corn: assessing potential agronomic, economic and environmental benefits. Plant Health Prog. 2004;10:423–430.
39. Pray C, Hunag J, Hu R, Roselle S. Five years of Bt cotton in China – the benefits continue. Plant J. 2002;31(4):423–30. doi:10.1046/j.1365-313X.2002.01401.x. PMID:12182701.
40. Gouse M, Pray C, Kirsten J, Schimmelpfennig D. A GM subsistence crop in Africa: the case of Bt white maize in S Africa. Int J Biotechnol. 2005;7(1/2/3):84–94. doi:10.1504/IJBT.2005.006447.
41. Gouse M, Piesse J, Thirtle C. Output & labour effect of GM maize and minimum tillage in a communal area of Kwazulu-Natal. J Dev Perspect. 2006;2(2):192–207.
42. Gouse M, Pray C, Kirsten J, Schimmelpfennig D. Three seasons of insect resistant maize in South Africa: have small farmers benefited. AgBioforum. 2006;9(1):15–22.
43. Van der Weld W. Final report on the adoption of GM maize in South Africa for the 2008/09 season, South African Maize Trust, 2009.
44. Ismael Y, Bennet R, Morse S. Benefits of bt cotton use by smallholder farmers in South Africa. Agbioforum. 2002;5(1):1–5.
45. Kirsten J, Gouse M. Bt cotton in South Africa: adoption and the impact on farm incomes amongst small-scale and large-scale farmers. ICABR conference, Ravello, Italy, 2002.
46. James C. Global review of commercialized transgenic crops 2002: feature Bt maize. ISAAA No 29, 2003.
47. Falck Zepeda J, Sanders A, Trabanino R, Medina O, Batallas-Huacon R. Small 'resource poor' countries taking advantage of the new bio-economy and innovation: the case of insect protected and herbicide tolerant corn in Honduras, 2009. paper presented to the 13th ICABR conference, Ravello, Italy, June 2009.
48. Falck Zepeda J, Sanders A, Trabanino R, Medina O, Batallas-Huacon R. Caught between Scylla and Charybdis: impact estimation issues from the early

adoption of GM maize in Honduras. Agbioforum. 2012;15(2):138–51.

49. Trigo E. Genetically Modified Crops in Argentina agriculture: an opened story. Buenos Aires, Argentina: Libros del Zorzal; 2002.
50. Qaim M, De Janvry A. Bt cotton in Argentina: analysing adoption and farmers' willingness to pay. 2002, American Agricultural Economics Association Annual Meeting, California.
51. Qaim M, De Janvry A. Bt cotton and pesticide use in Argentina: economic and environmental effects. Environ Dev Econ. 2005;10:179–200. doi:10.1017/S1355770X04001883.
52. Elena M. Economic advantages of transgenic cotton in Argentina, INTA. 2006, cited in Trigo and CAP 2006.
53. Gonsales L. Harnessing the benefits of biotechnology: the case of Bt corn in the Philippines. ISBN 971-91904-6-9. Laguna, Philippines: Strive Foundation; 2005.
54. Yorobe J. Economics impact of Bt corn in the Philippines. 2004, Paper presented to the 45th PAEDA Convention, Querzon City.
55. Ramon G. Acceptability survey on the 80–20 bag in a bag insect resistance management strategy for Bt corn. Biotechnology Coalition of the Philippines (BCP); 2005.
56. Brookes G. The farm level impact of using Bt maize in Spain. ICABR conference paper 2003, Ravello, Italy. Also on www.pgeconomics.co.uk.
57. Brookes G. The benefits of adopting GM insect resistant (Bt) maize in the EU: first results from 1998–2006. Int J Biotechnol. 2008;10(2/3):148–66. doi:10.1504/IJBT.2008.018351.
58. Gomez-Barbero M, Barbel J, Rodriguez-Cerezo E. Adoption and performance of the first GM crop in EU agriculture: Bt maize in Spain. 2008. JRC, EU Commission. Eur 22778. http://www.jrc.ec.europa.eu.
59. Riesgo L, Areal F, Rodriguez-Cerezo E. How can specific market demand for non-GM maize affect the profitability of Bt and conventional maize? A case study for the middle Ebro Valley, Spain. Spanish J Agric Res. 2012;10(4):867–76. doi:10.5424/sjar/2012104-448-11.
60. Herring R, Rao C. On the 'failure of Bt cotton': analysing a decade of experience. Econ Polit Wkly. 2012;47(18):5/5/2012.
61. Zambrano P. Insect resistant cotton in Colombia: impact on farmers. paper presented to the 13th ICABR conference, 2009, Ravello, Italy.
62. Vitale J, Glick H, Greenplate J, Traore O. The economic impact of 2nd generation Bt cotton in West Africa: empirical evidence from Burkina Faso. Int J Biotechnol. 2008;10(2/3):167–83. doi:10.1504/IJBT.2008.018352.
63. Vitale J. Impact of Bollgard II on the Socio Economic and Health Welfare of Smallholder Cotton Farmers in Burkina Faso. Results of the 2009 Field Survey14th ICABR conference, Ravello, Italy, June 2010.
64. Galveo A. Unpublished data on first survey findings of impact of insect resistant corn (first crop) in Brazil, 2009, Celeres, Brazil. www.celeres.co.br.
65. Monsanto Brazil. Farm survey of conventional and Bt cotton growers in Brazil 2007. unpublished.
66. Nazli H, Sarker R, Meilke K, Orden D. Economic performance of Bt cotton varieties in Pakistan. Conference paper at the Agricultural and Applied Economics Association 2010 AAEA, CAES and WACA Joint Annual Meeting, Denver, USA.
67. Kouser S, Qaim M. Valuing financial, health and environmental benefits of Bt cotton in Pakistan. Agric Econ. 2013;44:323–35. doi:10.1111/agec.12014.
68. Kouser S, Qaim M. Bt cotton, damage control and optimal levels of pesticide use in Pakistan. Environ Dev Econ. 2014;19(06):704–23. doi:10.1017/S1355770X1300051X.
69. USDA. New technologies aiding Burmese cotton farmers. GAIN report BM 0025 of 14th January 2011.
70. Doyle B. The Performance of Ingard and Bollgard II Cotton in Australia during the 2002/2003 and 2003/2004 seasons. Armidale, Australia: University of New England; 2005.
71. James C. Global review of commercialized transgenic crops 2001: feature Bt cotton. ISAAA No 26, 2002.
72. CSIRO. The cotton consultants Australia 2005 Bollgard II comparison report, CSIRO, Australia.
73. Fitt G. Deployment and impact of transgenic Bt cotton in Australia, reported in James C (2001), Global review of commercialised transgenic crops: 2001 feature: Bt cotton, ISAAA.
74. Monsanto Comercial Mexico. Official reports to Mexican Ministry of Agriculture of the (year) cotton crop, unpublished papers for 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016.
75. Traxler G, Godoy-Avila S. Transgenic cotton in Mexico. Agbioforum. 2004;7(1&2):57–62.
76. Weedscience.org. Website of International Survey of Herbicide Resistant Weeds. www.weedscience.org.

Appendix 1: Details of methodology as applied to 2016 farm income calculations

GM IR corn (targeting corn boring pests) 2016

Country	Area of trait ('000 ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price ($/tonne)	Cost of technology ($/ha)	Impact on costs, net of cost of technology ($/ha)	Change in farm income ($/ha)	Change in farm income at national level ('000 $)	Production impact ('000 tonnes)
US	27,734	+7	9.73	132	+25.74	+23.73	+66.38	+2,067,300	+20,600
Canada	1,048	+7	9.44	129	+26.0	+23.32	+61.96	+64,963	+693
Argentina	4,009	+5.5	8.0	165	+16.9	+16.9	+55.81	+223,728	+1,764
Philippines	653	+18	2.89	255	+42.0	+28.4	+104.10	+67,960	+339
South Africa	2,392	+10.6	5.43	213	+10.2	0.00	+122.75	+293,612	+1,377
Spain	129	+12.6	10.3	187	+38.72	+31.63	+182.1	+23,504	+168
Uruguay	46	+5.5	6.83	207	+16.94	+16.94	+60.77	+2,820	+17
Honduras	39	+24	3.38	159	+100.0	+100.0	+28.72	+1,112	+31
Portugal	7	+12.5	8.11	185	+38.72	+38.72	+149.12	+1,054	+7
Brazil	14,881	+11.1	5.08	185	+54.55	+41.08	+62.93	+936,426	+8,386
Colombia	80	+22	5.20	288	+42.19	−3.66	+333.67	+26,610	+91
Paraguay	300	+5.5	5.18	165	+16.05	+16.05	+31.05	+9,316	+85
Vietnam	35	+7.2	4.47	238	+38.57	+27.74	+104.47	+3,656	+11

Notes.

1. Impact on costs net of cost of technology = cost savings from reductions in pesticide costs, labour use, fuel use etc from which the additional cost (premium) of the technology has been deducted. For example (above) US cost savings from reduced expenditure on insecticides = −$15.88/ha, limited to an area equivalent to 10% of the total crop area (the area historically treated with insecticides for corn boring pests). This converted to an average insecticide cost saving equivalent per hectare of GM IR crop of -$2.01/ha. After deduction of the cost of technology (+$25.74/ha) is deducted to leave a net impact on costs of +$23.73

2. There are no Canadian-specific studies available, hence application of US study findings to the Canadian context (US being the nearest country for which relevant data is available)

GM IR corn (targeting corn rootworm) 2016

Country	Area of trait ('000 ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price ($/tonne)	Cost of technology ($/ha)	Impact on costs, net of cost of technology ($/ha)	Change in farm income ($/ha)	Change in farm income at national level ('000 $)	Production impact ('000 tonnes)
US	16,665	+5	9.73	132	+25.7	+3.14	+61.22	+1,019,084	+8,099
Canada	702	+5	9.44	129	+26	+7.28	+68.20	+47,893	+331

Notes.

1.There are no Canadian-specific studies available, hence application of US study findings to the Canadian context (US being the nearest country for which relevant data is available)

GM IR cotton 2016

Country	Area of trait ('000 ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price ($/tonne)	Cost of technology ($/ha)	Impact on costs, net of cost of technology ($/ha)	Change in farm income ($/ha)	Change in farm income at national level ('000 $)	Production impact ('000 tonnes)
US	3,232	+10	0.897	1,555	+44.95	+13.13	+126.39	+408,494	+290
China	2,755	+10	1.54	2,137	+55.19	−26.07	+359.50	+990,413	+430
South Africa	18	+24	.348	1,490	+23.45	−14.82	+130.86	+2,335	+1.5
Australia	551	Zero	1.58	1,863	+23.05	−188.20	+188.20	+103,740	Zero
Mexico	94	+10.5	1.46	1,606	+59.54	−38.48	+208.63	+19,611	+14
Argentina	221	+30	0.533	1,275	+21.25	−32.36	+236.23	+52,160	+35
India	10,416	+24	0.41	1,233	+11.91	+15.72	+146.22	+1,523,012	+1,102
Colombia	9	+10	0.525	1,628	+103.1	+50.7	+34.38	+304	+1
Brazil	511	+2.4	1.60	1,521	+27.18	−9.09	+66.90	+34,208	+19
Pakistan	2,328	+22	0.57	1,590	+3.87	−5.85	+207.35	+482,701	+295
Myanmar	223	+30	0.50	1,590	+20	+10.3	+226.32	+50,516	+33

Note Myanmar price based on Pakistan

GM HT soybeans 2016 (excluding second crop soybeans – see separate table)

Country	Area of trait ('000 ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price ($/tonne)	Cost of technology ($/ha)	Impact on costs, net of cost of technology ($/ha)	Change in farm income ($/ha)	Change in farm income at national level ('000 $)	Production impact ('000 tonnes)
US 1st generation	10,269	Nil	3.31	351	+57.49	−15.56	+15.56	+159,826	Nil
US 2nd generation	21,204	+8.9	3.31	351	+66.61	−6.45	+110.02	+2,332,937	+6,252
Canada 1st generation	776	Nil	2.84	343	+33.96	−15.55	+15.55	+12,072	Nil
Canada 2nd generation	1,142	+8.9	2.84	343	+53.52	+4.01	+82.60	+94,341	+289
Argentina	15,435	Nil	3.19	261	+2.5	−26.13	+26.13	+362,667	Nil
Brazil	15,406	Nil	3.36	332	+7.45	−40.05	+40.05	+502,167	Nil
Paraguay	1,683	Nil	3.15	335	+4.4	−22.75	+22.75	+30,889	Nil
South Africa	545	Nil	1.48	431	+1.02	−29.66	+29.66	+16,172	Nil
Uruguay	702	Nil	2.95	351	+2.5	−34.44	+34.44	+24,182	Nil
Mexico	3	−0.87	1.87	412	+47.31	−22.61	+5.96	+17	−0.1
Bolivia	1,028	+15	1.64	231	+3.32	−5.96	+52.11	+53,585	+252

Notes.

1. Price discount for GM soybeans relative to non GM soybeans in Bolivia of 2.7% – price for non GM soybeans was $237/tonne – price shown above is discounted
2. GM trait not available in leading varieties in Mexico

GM IR/HT (Intacta) soybeans 2016

Country	Area of trait (000′ ha)	Yield assumption % change	Base yield sucrose(tonnes/ ha)	Farm level price: $/tonne)	Cost of tech ($/ha)	Impact on costs, net of cost of tech ($/ha)	Change in farm income ($/ha)	Change in farm income at national level (‘000 $)	Production impact (‘000 tonnes)
Brazil	17,294	+9.4	3.19	332	+34.38	−16.45	+115.91	+2,004,604	+5,178
Argentina	3,162	+7.1	3.16	261	+29.87	−10.87	+69.36	+219,308	+709
Paraguay	1,485	+9.1	3.10	335	+29.87	−32.89	+157.53	+233,631	+552
Uruguay	359	+7	2.92	351	+29.87	−21.07	+93.02	+33,368	+74

GM HT corn 2016

Country	Area of trait ('000 ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price ($/tonne)	Cost of technology ($/ha)	Impact on costs, net of cost of technology ($/ha)	Change in farm income ($/ha)	Change in farm income at national level ('000 $)	Production impact ('000 tonnes)
US	31,245	Nil	10.27	132	+26.52	−38.77	+38.77	+1,212,107	Nil
Canada	1,285	Nil	9.96	129	+26.11	−18.43	+18.43	+23,686	Nil
Argentina: as single trait	599	+3% con belt, +22% marginal areas	9.05 corn belt, 5.43 marginal areas	165	+12.2	−3.36	+48.25 corn belt, +200.87 marginal areas	+83,941	+494
Argentina: as stacked trait	3,594	+10.25	8.0	165	+21.7	−5.82	+129.75	+466,363	+2,947
South Africa	1,928	Nil	5.95	213	+10.88	−9.04	+9.04	+17,426	Nil
Philippines	655	+5	2.89	255	+42.11	+14.86	+21.96	+14,391	+95
Colombia	86	Zero	5.43	288	+18.66	−13.22	+13.22	+1,137	Nil
Brazil	11,908	+3	5.08	185	+10.97	+4.45	+23.75	+282,826	+1,819
Uruguay	49	Nil	7.14	207	+12.20	−3.67	+3.67	+179	Nil
Paraguay	260	Nil	5.30	165	+12.96	+5.90	+5.90	+1,535	Nil
Vietnam	35	+5	4.47	238	+25.71	+16.25	+37.03	+1,296	+8

Notes.

1. Where no positive yield effect due to this technology is applied, the base yields shown are the indicative average yields for the crops and differ (are higher) than those used for the GM IR base yield analysis, which have been adjusted downwards to reflect the impact of the yield enhancing technology (see below)

2. Argentina: single trait. In the Corn Belt it is assumed that 70% of trait plantings occur in this region and marginal regions account for the balance. In relation to stacked traits, the yield impact (+10.25%) is in addition to the yield 5.5% impact presented for the GM IR trait (above). In other words the total estimated yield impact of stacked traits is +15.75%. The cost of the technology also relates specifically to the HT part of the technology (sold within the stack)

GM HT cotton 2016

Country	Area of trait ('000 ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price ($/tonne)	Cost of technology ($/ha)	Impact on costs, net of cost of technology ($/ha)	Change in farm income ($/ha)	Change in farm income at national level ('000 $)	Production impact ('000 tonnes)
US	3,425	Nil	0.972	1,512	+67.42	−10.72	+10.72	+36,719	Nil
S Africa	18	Nil	0.43	1,744	+14.9	−22.81	+22.81	+407	Nil
Australia	568	Nil	1.58	1,863	−58.74	−24.86	+24.86	+14,128	Nil
Argentina	240	Farm saved seed area nil Certified seed area +9.3%	0.68	1,275	+11.16 certified seed, nil farm saved seed	−5.86 certified seed, −17.02 farm saved seed	+ 86.47 certified seed, +17.02 farm saved seed	+9,183	+5
Mexico	98	+19.6	1.46	1,606	+44.2	−26.65	+433.0	+42,423	+28
Colombia	9	+4.0	0.525	1,620	+110.1	−18.13	+52.16	+473	+0.1
Brazil	623	+1.6	1.60	1,521	+27.18	−4.04	+42.98	+26,783	+16

Notes.

1.Where no positive yield effect due to this technology is applied, the base yields shown are the indicative average yields for the crops and differ (are higher) than those used for the GM IR base yield analysis, which have been adjusted downwards to reflect the impact of the yield enhancing technology (see below)

2.Argentina: 30% of area assumed to use certified seed with 70% farm saved seed

GM HT canola 2016

Country	Area of trait ('000 ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price ($/tonne)	Cost of technology ($/ha)	Impact on costs, net of cost of technology ($/ha)	Change in farm income ($/ha)	Change in farm income at national level ('000 $)	Production impact ('000 tonnes)
US glyphosate tolerant	295	+2.6	1.96	370	+17.3	−6.48	+25.40	+7,485	+20
US glufosinate tolerant	319	+7.3	1.96	370	+17.3	+9.37	+43.73	+13,963	+38
Canada glyphosate tolerant	3,264	+2.6	2.3	399	+27.92	−6.04	+29.86	+97,466	+195
Canada glufosinate tolerant	4,417	+7.3	2.3	399	Nil	−18.11	+85.00	+375,421	+740
Australia glyphosate tolerant	445	+8	1.57	374	+9.67	+0.97	+34.66	+15,516	+41

Note: Baseline (conventional) comparison in Canada with herbicide tolerant (non GM) 'Clearfield' varieties

GM virus resistant crops 2016

Country	Area of trait (ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price ($/tonne)	Cost of technology ($/ha)	Impact on costs, net of cost of technology ($/ha)	Change in farm income ($/ha)	Change in farm income at national level (‘000 $)	Production impact (‘000 tonnes)
US Papaya	395	+17	23.86	924	+494	+494	+3,254	+1,284	+1.6
US squash	1,000	+100	21.22	526	+736	+736	+10,416	+10,416	+21

GM herbicide tolerant sugar beet 2016

Country	Area of trait (000′ ha)	Yield assumption % change	Base yield sucrose(tonnes/ha)	Farm level price equivalent (sucrose: $/tonne)	Cost of tech ($/ha)	Impact on costs, net of cost of tech ($/ha)	Change in farm income ($/ha)	Change in farm income at national level (‘000 $)	Production impact (‘000 tonnes)
US	456	+3.58	10.35	279	+148	−2.55	+105.95	+48,291	+169
Canada	12	+3.58	12.17	279	+148	−2.55	+124.13	+1,437	+5

GM drought tolerant maize 2016

Country	Area of trait (000′ ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price equivalent (sucrose: $/tonne)	Cost of tech ($/ha)	Impact on costs, net of cost of tech ($/ha)	Change in farm income ($/ha)	Change in farm income at national level (‘000 $)	Production impact (‘000 tonnes)
US	1,349	+2.57	9.73	132	+18.30	+18.23	+14.86	+20,046	+337

Second soybean crop benefits: Argentina

An additional farm income benefit that many Argentine soybean growers have derived comes from the additional scope for second cropping of soybeans. This has arisen because of the simplicity, ease and weed management flexibility provided by the (GM) technology which has been an important factor facilitating the use of no and reduced tillage production systems. In turn the adoption of low/no tillage production systems has reduced the time required for harvesting and drilling subsequent crops and hence has enabled many Argentine 27 farmers to cultivate two crops (wheat followed by soybeans) in one season. As such, the proportion of soybean production in Argentina using no or low tillage methods has increased from 34% in 1996 to 90% by 2005 and has remained at over 90%since then.

Farm level income impact of using GM HT soybeans in Argentina 2016 (2): second crop soybeans

Year	Second crop area (million ha)	Average gross margin/ha for second crop soybeans ($/ha)	Increase in income linked to GM HT system (million $)
2016	5.2	140.80	732.2

Source & notes.

1.Crop area and gross margin data based on data supplied by Grupo CEO and the Argentine Ministry of Agriculture

2.The second cropping benefits are based on the gross margin derived from second crop soybeans multiplied by the total area of second crop soybeans

Base yields used where GM technology delivers a positive yield gain

In order to avoid over-stating the positive yield effect of GM technology (where studies have identified such an impact) when applied at a national level, average (national level) yields used have been adjusted downwards (see example below). Production levels based on these adjusted levels were then cross checked with total production values based on reported average yields across the total crop.

Example: GM IR cotton (2016)

Country	Average yield across all forms of production (t/ha)	Total cotton area (‘000 ha)	Total production (‘000 tonnes)	GM IR area (‘000 ha)	Conventional area (‘000 ha)	Assumed yield effect of GM IR technology	Adjusted base yield for conventional cotton (t/ha)	GM IR production (‘000 tonnes)	Conventional production (‘000 tonnes)
US	0.972	3,848	3,740	3,232	616	+10%	0.897	3,189	552
China	1.708	2,900	4,953	2,755	145	+10%	1.56	4,727	226

Note: Figures subject to rounding