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Economic impact of GM crops
The global income and production effects 1996–2012

Graham Brookes* and Peter Barfoot

PG Economics Ltd; Dorchester, UK

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

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A key part of any assessment of the global value of crop biotechnology in agriculture is an examination of its economic impact at the farm level. This paper follows earlier annual studies which examined economic impacts on yields, key costs of production, direct farm income and effects, and impacts on the production base of the four main crops of soybeans, corn, cotton and canola. The commercialization of genetically modified (GM) crops has continued to occur at a rapid rate, with important changes in both the overall level of adoption and impact occurring in 2012. This annual updated analysis shows that there have been very significant net economic benefits at the farm level amounting to $18.8 billion in 2012 and $116.6 billion for the 17-year period (in nominal terms). These economic gains have been divided roughly 50% each to farmers in developed and developing countries. GM technology have also made important contributions to increasing global production levels of the four main crops, having added 122 million tons and 230 million tons respectively, to the global production of soybeans and maize since the introduction of the technology in the mid-1990s.

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Introduction

Although the first commercial genetically modified (GM) crops were planted in 1994 (tomatoes), 1996 was the first year in which a significant area of crops containing GM traits was planted (1.66 million hectares). Since then there has been a significant increase in plantings and by 2012, the global planted area reached over 160 million hectares.

Since the mid-1990s, there have been many papers assessing the economic impacts associated with the adoption of this technology, at the farm level. 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 and appropriate, 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 economic impacts associated with the global adoption of GM crops. It is also hoped the analysis contributes to greater understanding of the impact of this technology and facilitates more informed decision making, especially in countries where crop biotechnology is currently not permitted.

Therefore, integrating the data for 2012 into the context of earlier developments, this study updates the findings of earlier analysis into the global economic impact of GM crops since their commercial introduction in 1996. Earlier analysis by the current authors has been published in various journals, including *AgbioForum*,[1] *International Journal of Biotechnology*,[2] and *GM Crops and Food*.[3,4] 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 the chore of consulting these earlier papers for details of the methodology and arguments, these are included in full in this updated paper.

The analysis concentrates on farm income effects because this is a primary driver of adoption among farmers (both large commercial and small-scale subsistence). It also quantifies the (net) production impact of the technology. The authors recognize that an economic assessment could examine a broader range of potential impacts (e.g., on labor usage, households, 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 economic assessment of wider economic impacts would probably merit a separate assessment in its own right.

Results and Discussion

HT crops

The primary impact of GM HT (largely tolerant to the broad spectrum herbicide glyphosate) technology has been to provide

*Correspondence to: Graham Brookes; Email: graham.brookes@btinternet.com
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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 vs. conventional alternatives, the mix and amount 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, however, be noted:

- In the period 2008–2009, the average cost associated with the use of GM HT technology globally increased relative to earlier years because of the significant increase in the global price of glyphosate relative to changes in the price of other herbicides commonly used on conventional crops. This has abated since 2009 with a decline in the price of glyphosate to previous historic trend levels.
- The amount farmers pay for use of the technology varies by country. Pricing of technology (all forms of seed and crop protection 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 the next bullet point.
- 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.org). Worldwide, there are 25 weed species that are currently (accessed December 2013) resistant to glyphosate, compared with 135 weed species resistant to ALS herbicides (e.g., chlorimuron ethyl commonly used in conventional soybean crops) and 72 weed species resistant to photosystem II inhibitor herbicides (e.g., atriazine commonly used in corn production). In addition, it should be noted that the adoption of 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 toward those weed species that are not well controlled by glyphosate. As a result, 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 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 minimize and slow down the potential for weeds developing resistance to existing technology solutions. At the macro level, these changes have already begun to influence the mix, total amount, cost, and overall profile of herbicides applied to GM HT crops. Relative to the conventional alternative, however, the economic impact of the GM HT crop use has continued to offer important advantages. Also, many of the herbicides used in conventional production systems had significant resistance issues themselves in the mid-1990s. This was, for example, 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 favor 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 average impacts on farm level profitability from using this technology are summarized in **Table 1**. The main farm level gain experienced has been a reduction in the cost of production, mainly through reduced expenditure on weed control (herbicides). Not surprisingly, where yield gains have occurred from improvements in the level of weed control, the average farm income gain has tended to be higher, in countries such as Romania, Mexico, and 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 realization of this potential is shown in the higher average 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. This second crop, additional to traditional soybean production, has added considerably to farm incomes and to the volumes of soybean production in countries such as Argentina and Paraguay (**Table 1**).

Overall, in 2012, GM HT technology in soybeans has boosted farm incomes by $4.8 billion, and since 1996 has delivered $37 billion of extra farm income. Of the total cumulative farm income gains from using GM HT soybeans, $13.9 billion (38%) has been due to yield gains and/or second crop benefits, and the balance, 62%, has been due to cost savings.

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, and the Philippines (**Table 2**).

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Table 1. GM HT soybeans: summary of average farm level economic impacts 1996–2012 ($/hectare)

Country	Cost of technology	Average farm income benefit (after deduction of cost of technology)	Type of benefit	References
1st generation GM HT soybeans				
Romania (to 2006 only)	50–60	104	Small cost savings of about $9/ha, balance due to yield gains of +13% to +31%	Brookes (2005)[5] Monsanto Romania (2007)[6]
Argentina	2–4	22 plus second crop benefits of 213	Cost savings plus second crop gains	Qaim and Trazler (2005)[7] Trigo and CAP (2006)[8] and updated from 2008 to reflect herbicide price changes
Brazil	11–25	34	Cost savings	Parana Department of Agriculture (2004)[9] Galveo (2010, 2012, and 2013)[10-12]
USA	15–39	38	Cost savings	Marra et al. (2002)[13] Carpenter and Gianessi (2002)[14] Sankala and Blumenthal (2003 and 2006)[15,16] Johnson and Strom (2008)[17] And updated to reflect herbicide price and common product usage
Canada	20–40	20	Cost savings	George Morris Center (2004)[18] and updated to reflect herbicide price and common product usage
Paraguay	4–10	17 plus second crop benefits of 213	Cost savings	Based on Argentina as no country-specific analysis identified; impacts confirmed by industry sources and herbicide costs updated 2009 onwards from herbicide usage survey data (AMIS Global)
Uruguay	2–4	22	Cost savings	Based on Argentina as no country-specific analysis identified. Impacts confirmed by industry sources and herbicide costs updated 2009 onwards from herbicide usage survey data (AMIS Global)
South Africa	20–30	4	Cost savings	As there are no published studies available, based on data from industry sources and herbicide costs updated 2009 onwards from herbicide usage survey data (AMIS Global)
Mexico	20–25	48	Cost savings plus yield gain in range of +2% to +13%	Monsanto unpublished annual monitoring reports and personal communications
Bolivia	3–4	80	Cost savings plus yield gain of +15%	Fernandez W et al. (2009)[19]
2nd[t] generation GM HT soybeans				
US and Canada	47–65	149 (US) 129 (Can)	Cost savings as first generation plus yield gains in range of +5% to +11%	As first generation GM HT soybeans plus farm level survey data from Monsanto USA (2011 and 2012)

(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) For additional details of how impacts have been estimated, see examples in Supplemental Materials, Appendix 1.

In 2012, the total global farm income gain from using this technology was $1.2 billion with the cumulative gain over the period 1996–2012 being $5.4 billion. Within this, $1.4 billion (26%) was due to yield gains and the rest derived from lower costs of production (**Table 2**).

GM HT cotton

The use of GM HT cotton delivered a net farm income gain of about $147 million in 2012. In the 1996–2012 period, the total farm income benefit was $1.37 billion. As with other GM HT traits, these farm income gains have mainly arisen from cost

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Table 2. GM HT maize: summary of average farm level economic impacts 1996–2012 ($ per hectare)

Country	Cost of technology	Average farm income benefit (after deduction of cost of technology)	Type of benefit	References
USA	15–30	21	Cost savings	Carpenter and Gianessi (2002)[14] Sankala and Blumenthal (2003 and 2006)[15,16] Johnson and Strom (2008)[17] Also updated annually to reflect herbicide price and common product usage
Canada	17–35	11	Cost savings	Monsanto Canada (personal communications) and updated annually since 2008 to reflect changes in herbicide prices and usage
Argentina	16–20	90	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	10–18	1	Cost savings	Personal communication from Monsanto South Africa and updated since 2008 to reflect changes in herbicide prices and usage
Brazil	17–32	58	Cost savings plus yield gains of +1% to +7%	Galveo (2010, 2012, and 2013)[10-12])
Colombia	22–24	17	Cost savings	Mendez et al. (2011)[20]
Philippines	24–47	40	Cost savings plus yield gains of +5% to +15%	Gonsales et al. (2009)[21] Monsanto Philippines (personal communications) Updated since 2010 to reflect changes in herbicide prices and usage

(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 Supplemental Materials, Appendix 1.

savings (84% of the total gains), although there have been some yield gains in 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, while GM HT sugar beet is grown in the US and Canada. The farm income impacts associated with the adoption of these technologies are summarized in **Table 4**. In both cases, the main farm income benefit has derived from yield gains. In 2012, the total global income gain from the adoption of GM HT technology was $481 million and cumulatively since 1996, it was $3.66 billion (**Table 4**).

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 typically been least effective (e.g., reasons such as less well-developed extension and advisory services and/or lack of access to finance to fund use of crop protection application equipment and 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 farm income gains from using GM IR maize and cotton in 2012 were $6.71 billion and $5.3 billion respectively. Cumulatively since 1996, the gains have been $32.3 billion for GM IR maize and $36.3 billion for GM IR cotton.

Aggregated (global level) impacts

At the global level, GM technology has had a significant positive impact on farm income, with in 2012, the direct global farm income benefit being $18.8 billion. This is equivalent to having added 6% to the value of global production of the four main crops of soybeans, maize, canola, and cotton. Since 1996, farm incomes have increased by $116.6 billion.

At the country level, US farmers have been the largest beneficiaries of higher incomes, realizing over $53.2 billion in extra income between 1996 and 2012. This is not surprising given that US farmers were first to make widespread use of GM crop technology and for several years the GM adoption levels in all four US crops have been in excess of 80%. Important farm income benefits ($25.4 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 $29.8 billion additional income for cotton farmers in China and India.

In 2012, 46.6% 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

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Table 3. GM HT cotton summary of average farm level economic impacts 1996–2012 ($/hectare)

Country	Cost of technology	Average farm income benefit (after deduction of cost of technology)	Type of benefit	References
USA	13–82	22	Cost savings	Carpenter and Gianessi (2002)[14] Sankala and Blumenthal (2003 and 2006)[15,16] Johnson and Strom (2008)[17] Also updated to reflect herbicide price and common product usage
South Africa	15–32	33	Cost savings	Personal communication from Monsanto South Africa and updated since 2008 to reflect changes in herbicide prices and usage
Australia	32–131	30	Cost savings	Doyle et al. (2003)[22] Monsanto Australia (personal communications) and updated to reflect changes in herbicide usage and prices
Argentina	17–30	40	Cost savings	Personal communication from Monsanto Argentina, Grupo CEO and updated since 2008 to reflect changes in herbicide prices and usage
Brazil	37–52	91	Cost savings plus yield gains of +2% to +4% (-2% 2012)	Galveo (2010, 2012, and 2013)[10-12]
Mexico	29–72	177	Cost savings plus yield gains of +3% to +18%	Monsanto Mexico annual monitoring reports[8] and personal communications
Colombia	96–187	101	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 (e.g., 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 Supplemental Materials, Appendix 1.

17 years, 1996–2012, the cumulative farm income gain derived by developing country farmers was $58.15 billion, equal to 49.9% of the total farm income during this period.

The cost to farmers for accessing GM technology, across the four main crops, in 2012, was equal to 23% 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 21% of total technology gains compared with 25% in developed countries. While 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 with those in developed countries.

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 corn, cotton, canola, and soybeans since 1996 (**Table 7**).

The GM IR traits, used in maize and cotton, have accounted for 96.1% 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 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 with 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 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 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 106.4 million tonnes to soybean production in Argentina

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Table 4. Other GM HT crops summary of average farm level economic impacts 1996–2012 ($ per hectare)

Country	Cost of technology	Average farm income benefit (after deduction of cost of technology)	Type of benefit	References
GM HT canola				
US	12–33	52	Mostly yield gains of +1% to +12% (especially Invigor canola)	Sankala and Blumenthal (2003 and 2006)[15,16] Johnson and Strom (2008)[17] And updated to reflect herbicide price and common product usage
Canada	18–32	51	Mostly yield gains of +3% to +12% (especially Invigor canola)	Canola Council (2001)[23] Gusta et al. (2009)[24] and updated to reflect herbicide price changes and seed variety trial data (on yields)
Australia	22–41	55	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 (2009)[25], Fischler and Tozer (2009),[26] and Hudson (2013)[27]
GM HT sugar beet				
US and Canada	130–151	110	Mostly yield gains of +3% to +13%	Kniss (2008)[28] Khan (2008)[29] Jon-Joseph et al. (2010)[30] 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's 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 Supplemental Materials, Appendix 1.

and Paraguay between 1996 and 2011 (accounting for 96.6% of the total GM-related additional soybean production) (**Table** 7).

Concluding Comments

During the past 17 years, the adoption of crop biotechnology (by 17.3 million farmers in 2012) has delivered important economic benefits. The GM IR traits have mostly delivered higher incomes through improved yields in all countries. Many farmers, especially in developed countries, have also benefited from lower costs of production (less expenditure on insecticides). The gains from GM HT traits have come from a combination of effects. The GM HT technology-driven farm income gains have mostly arisen from reduced costs of production, though in South America, it facilitated the move away from conventional to low and/or no-tillage production systems and enabled many farmers to plant a second crop of soybeans after wheat in the same season.

Over-reliance on the use of glyphosate and the lack of crop rotation by some farmers, in some regions, has contributed to the development of weed resistance. As a result, farmers are increasingly adopting a mix of reactive and proactive weed management strategies incorporating a mix of herbicides. This has added cost to the GM HT production systems compared with several years ago, although relative to the conventional alternative, the GM HT technology continues to offer important economic benefits in 2012.

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

Methodology

The report is based on extensive analysis of existing farm level impact data for GM crops, much of which can be found in peer reviewed literature. While 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. In addition, the authors have undertaken their own analysis of the impact of some trait-crop

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Table 5. Average (%) yield gains GM IR cotton and maize 1996–2012

	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 (2002)[14] Marra et al. (2002)[13] Sankala and Blumenthal (2003 and 2006)[15,16] Hutchison et al. (2010)[31] Rice (2004)[32]
China	N/a	N/a	10.0	Pray et al. (2002)[33] Monsanto China (personal communications)
South Africa	11.6	N/a	24.0	Gouse et al. (2005, 2006a, and 2006b)[34-36] Van der Wald (2010)[37] Ismael et al. (2002)[38] Kirsten et al. (2002)[39] James (2003)[40]
Honduras	23.6	N/a	N/a	Falk Zepeda et al. (2009 and 2012)[41,42]
Mexico	N/a	N/a	10.0	Traxler et al. (2001)[43] Monsanto Mexico annual cotton monitoring reports[8]
Argentina	6.3	N/a	30.0	Trigo (2002)[43] Trigo and Cap (2006)[8] Qaim and De Janvry (2002 and 2005)[44,45] Elena (2001)[46]
Philippines	18.4	N/a	N/a	Gonsales (2005)[47] Gonsales et al. (2008)[21] Yorobe (2004)[48] Ramon (2005)[49]
Spain	10.4	N/a	N/a	Brookes (2003 and 2008)[50,51] Gomez-Barbero and Rodriguez-Corejo (2006)[52] Riesgo et al. (2012)[53]
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	36.0	Bennett et al. (2004)[54] IMRB (2006 and 2007)[55,56] Herring and Rao (2012)[57]
Colombia	21.4	N/a	21.0	Mendez et al. (2011)[20] Zambrano et al. (2009)[58]
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. (2008 and 2010)[59,60]
Brazil	13.0	N/a	-1	Galveo (2009, 2010, 2012, and 2013)[61,10,11,62]) Monsanto Brazil (2008)[63]
Pakistan	N/a	N/a	20.0	Nazli et al. (2010)[64] and Kouser and Qaim (2013)[65,66]
Burma	N/a	N/a	30.0	USDA (2011)[67]
Australia	N/a	N/a	Nil	Doyle (2005)[68] James (2002)[69] CSIRO (2005)[70] Fitt (2001)[71]

Notes: N/a, not applicable

combinations in some countries (notably GM herbicide tolerant [HT] traits in North and South America) based on herbicide usage and cost data over the last five years.

As indicated in earlier papers, the economic impact of this technology at the farm level varies widely, both between and within regions and/or countries. Therefore the measurement

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Table 6. GM IR crops: average farm income benefit 1996–2012 ($/hectare)

Country	GM IR maize: cost of technology	GM IR maize (average farm income benefit (after deduction of cost of technology)	GM IR cotton: cost of technology	GM IR cotton (average farm income benefit (after deduction of cost of technology)
US	17–32 IRCB, 22–42 IR CRW	87 IRCB, 89 IR CRW	26–58	107
Canada	17–25 IRCB, 22–42 IR CRW	89 IRCB 106 IR CRW	N/a	N/a
Argentina	20–33	19	26–86	191
Philippines	30–47	94	N/a	N/a
South Africa	8–17	80	14–50	192
Spain	17–51	214	N/a	N/a
Uruguay	20–33	26	N/a	N/a
Honduras	100	61	N/a	N/a
Colombia	43–49	247	50–175	67
Brazil	54–69	83	34–52	8
China	N/a	N/a	38–60	361
Australia	N/a	N/a	85–299	211
Mexico	N/a	N/a	48–70	182
India	N/a	N/a	15–54	252
Burkina Faso	N/a	N/a	51–54	201
Burma	N/a	N/a	17–20	176
Pakistan	N/a	N/a	4–15	77
Average across all user countries		**81**		**230**

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 (e.g., 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) Colombia, GM IR maize are farm level trials only. (4) Average across all countries is a weighted average based on areas planted in each user country. (5) n/a, not applicable.

Table 7. 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	12.05
Corn	230.5	34.09
Cotton	18.2	2.39
Canola	6.6	0.40
Sugar beet	0.6	0.15

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

of impact is considered on a case-by-case basis in terms of crop and trait combinations and is based on the average performance and impact recorded in different crops by the studies reviewed. Where more than one piece of relevant research (e.g., 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 and/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 are 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 comparisons from several years ago 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. Therefore to reduce the possibilities of overstating and/or 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

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vary in many cases according to the findings of literature covering different years. Examples where such data are available include the impact of GM insect resistant (IR) cotton: in India (see Bennett R et al.[54] and IMRB,[55,56]), in Mexico (see Traxler et al.[72] and Monsanto Mexico[73]), and in the US (see Sankala and Blumenthal,[15,16] and Mullins and Hudson[74]). 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. In this way a degree of dynamic has been introduced into the analysis that would, otherwise, be missing if constant prices and average yields identified in year-specific studies had been used.
- As indicated above, 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, and databases of crop protection usage and prices), and some "own analysis" of changes in crop protection usage and prices.
- 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 the calculation of the 2012 year results are presented in **Supplemental Materials, Appendix 1**. **Supplemental Materials, Appendix 2** also provides details of the impacts and assumptions applied and their sources.

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 analyzed 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 labor). 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. Therefore, in most cases the analysis relates to impact of crop protection and seed cost only, crop quality (e.g., improvements in quality arising from less pest damage or lower levels of weed impurities which result in price premiums being obtained from buyers), and the scope for facilitating the planting of a second crop in a season (e.g., 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 calculated (for 2012) are shown in **Supplemental Materials, Appendix 1**.

Disclosure of Potential Conflicts of Interest

No potential conflict of interest was disclosed.

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Supplemental Materials

Supplemental materials may be found here:
www.landesbioscience.com/journals/gmcrops/article/28098

References

1. Brookes G, Barfoot P. Global impact of biotech crops: socio-economic effects 1996-2007. Agbioforum 2009; 12:184-208
2. Brookes G, Barfoot P. The income and production effects of biotech crops globally 1996-2009. Int J Biotechnol 2011; 12:1-49; http://dx.doi.org/10.1504/IJBT.2011.042680
3. Brookes G, Barfoot P. The income and production effects of biotech crops globally 1996-2010. GM Crops Food 2012; 3:265-72; PMID:22750951; http://dx.doi.org/10.4161/gmcr.20097
4. Brookes G, Barfoot P. The income and production effects of biotech crops globally 1996-2010. GM Crops 2013; 4:1-10
5. Brookes G. The farm level impact of using Roundup Ready soybeans in Romania. Agioforum 2005: 8; 1-27
6. Monsanto Romania. (2007) Unpublished results of farmer survey amongst soybean growers in 2006.
7. Qaim M, Traxler G. Roundup Ready soybeans in Argentina: farm level & aggregate welfare effects. Agric Econ 2005; 32:73-86; http://dx.doi.org/10.1111/j.0169-5150.2005.00006.x
8. Trigo E, Cap E. (2006) Ten years of GM crops in Argentine Agriculture, ArgenBio.
9. Cost of production comparison: biotech and conventional soybeans, in USDA GAIN report BR4629 of 11 November 2004 [Internet]. Washington (DC); Parana Department of Agriculture: c2004 [cited 2 Jan 2014]. Available from: www.fas.usad.gov/gainfiles/200411/146118108.pdf
10. Galveo A. Farm survey findings of impact of insect resistant corn and herbicide tolerant soybeans in Brazil, Celeres, Brazil [Internet]. Uberlandia (Brazil): Celeres: c2010 [cited 2 Jan 2014]. Available from: www.celeres.co.br

©2014 Landes Bioscience. Do not distribute.

11. Galveo A. Farm survey findings of impact of GM crops in Brazil 2011, Celeres, Brazil [Internet]. Uberlandia (Brazil): Celeres: c2012 [cited 2 Jan 2014]. Available from: www.celeres.co.br
12. Galveo A. Farm survey findings of impact of GM crops in Brazil 2012, Celeres, Brazil [Internet]. Uberlandia (Brazil): Celeres: c2013 [cited 2 Jan 2014]. Available from: www.celeres.co.br
13. Marra M, Pardey P, Alston J. (2002) The pay-offs of agricultural biotechnology: an assessment of the evidence. International Food Policy Research Institute; Washington, USA.
14. Carpenter J, Gianessi L. (2002) Agricultural Biotechnology: updated benefit estimates. National Centre for Food and Agricultural Policy (NCFAP); Washington, USA.
15. Sankala S, Blumenthal E. Impacts on US agriculture of biotechnology-derived crops planted in 2003- an update of eleven case studies, NCFAP, Washington [Internet]. Washington (DC): NCFAP: c2003 [cited 2 Jan 2014]. Available from: www.ncfap.org
16. Sankala S, Blumenthal E. Impacts on US agriculture of biotechnology-derived crops planted in 2005- an update of eleven case studies, NCFAP, Washington [Internet]. Washington (DC): NCFAP: c2006 [cited 2 Jan 2014]. Available from: www.ncfap.org
17. Johnson S, Strom S. Quantification of the impacts on US agriculture of biotechnology-derived crops planted in 2006, NCFAP, Washington [Internet]. Washington (DC): NCFAP: c2008 [cited 2 Jan 2014]. Available from: www.ncfap.org
18. George Morris Centre. (2004) Economic & environmental impacts of the commercial cultivation of glyphosate tolerant soybeans in Ontario, unpublished report for Monsanto Canada.
19. Fernandez W, et al. (2009) GM soybeans in Bolivia, paper presented to the 13th ICABR conference, Ravello, Italy, June 2009.
20. Méndez KA, Chaparro Giraldo A, Moreno GR, Castro CS. Production cost analysis and use of pesticides in the transgenic and conventional corn crop [Zea mays (L.)] in the valley of San Juan, Tolima. GM Crops 2011; 2:163-8; PMID:22008311; http://dx.doi.org/10.4161/gmcr.2.3.17591
21. Gonzales LA, Javier EQ, Ramirez DA, Cariño FA, Baria AR. Modern Biotechnology and Agriculture: a history of the commercialization of biotechnology maize in the Philippines. Los Banos, Philippines; Strive Foundation; 2009.
22. Doyle B, Traxler G. The Performance of Roundup Ready cotton 2001-2002 in the Australian cotton sector. Armidale, Australia; University of New England; 2003.
23. An agronomic & economic assessment of transgenic canola, Canola Council, Canada [Internet]. Edmonton (Canada): Canada Council of Canola: c2001 [cited 2 Jan 2014]. Available from: www.canola-council.org
24. Gusta M, et al. (2009) Economic benefits of GMHT canola for producers, University of Saskatchewan, College of Biotechnology Working Paper.
25. Monsanto Australia (2009) Survey of herbicide tolerant canola licence holders 2008.
26. Fischer J, Tozer P. (2009) Evaluation of the environmental and economic impact of Roundup Ready canola in the Western Australian crop production system, Curtin Univeristy of Technology Technical Report 11/2009.
27. Hudson D. (2013) Evaluation of agronomic, environmental, economic and co-existence impacts following the introduction of GM canola in Australia 2010-2012. Paper presented to the 2012 GMCC conference, Lisbon, Portugal, November 2013.
28. Kniss A. (2009) Farm scale analysis of glyphosate resistant sugar beet in the year of commercial introduction in Wyoming. University of Wyoming.
29. Khan M. Roundup Ready sugar beet in America. British Sugar Beet Review 2008; 76:16-9
30. Jon-Joseph Q, et al. Weed management in wide-and narrow-row glyphosate resistant sugar beet. Weed Technol 2010; 24:523-8; http://dx.doi.org/10.1614/WT-D-10-00033.1
31. Hutchison WD, Burkness EC, Mitchell PD, Moon RD, Leslie TW, Fleischer SJ, Abrahamson M, Hamilton KL, Steffey KL, Gray ME, et al. Areawide suppression of European corn borer with Bt maize reaps savings to non-Bt maize growers. Science 2010; 330:222-5; PMID:20929774; http://dx.doi.org/10.1126/science.1190242
32. Rice M. Transgenic rootworm corn: assessing potential agronomic, economic and environmental benefits. Plant Health Progress 2004; 10,094:php-2001-0301-01-RV.
33. Pray CE, Huang J, Hu R, Rozelle S. Five years of Bt cotton in China - the benefits continue. Plant J 2002; 31:423-30; PMID:12182701; http://dx.doi.org/10.1046/j.1365-313X.2002.01401.x
34. Gouse M, et al. A GM subsistence crop in Africa: the case of Bt white maize in S Africa. Int J Biotechnol 2005; 7; http://dx.doi.org/10.1504/IJBT.2005.006447
35. Gouse M, et al. Output & labour effect of GM maize and minimum tillage in a communal area of Kwazulu-Natal. Journal of Development Perspectives 2006; 2:2
36. Gouse, et al. Three seasons of insect resistant maize in South Africa: have small farmers benefited. AgBioforum 2006; 9:15-22
37. Van der Weld W. (2009) Final report on the adoption of GM maize in South Africa for the 2008/09 season. South African Maize Trust.
38. Ismael Y et al (2002) A case study of smallholder farmers in the Mahathini flats, South Africa, ICABR conference, Ravello Italy 2002.
39. Kirsten J, et al. (2002) Bt cotton in South Africa: adoption and the impact on farm incomes amongst small-scale and large-scale farmers, ICABR conference, Ravello, Italy 2002.
40. James C (2003) Global review of commercialized transgenic crops 2002: feature Bt maize. ISAAA No 29.
41. Falck Zepeda J, et al. (2009) Small 'resource poor' countries taking advantage of the new bio-economy and innovation: the case of insect protected and herbicide tolerant corn in Honduras, paper presented to the 13th ICABR conference, Ravello, Italy, June 2009.
42. Falk-Zepeda J et al (2012) Caught between Scylla and Charybdis: impact estimation issues from the early adoption of GM maize in Honduras.
43. Trigo EJ, et al. Genetically Modified Crops in Argentina agriculture: an opened story. Buenos Aires: Libros del Zorzal: 2002.
44. Qaim M, De Janvry A. (2002) Bt cotton in Argentina: analysing adoption and farmers willingness to pay. American Agricultural Economics Association Annual Meeting, California
45. Qaim M, De Janvry A. Bt cotton and pesticide use in Argentina: economic and environmental effects. Environ Dev Econ 2005; 10:179-200; http://dx.doi.org/10.1017/S1355770X04001883
46. Elena M (2001) Economic advantages of transgenic cotton in Argentina, INTA, cited in Trigo & Cap (2006)
47. Gonsales L. Harnesing the benefits of biotechnology: the case of Bt corn in the Philippines. Laguna (Philippines): Strive Foundation: 2005.
48. Yorobe J. (2004) Economics impact of Bt corn in the Philippines. Paper presented to the 45th PAEDA Convention, Querzon City.
49. Ramon G. Acceptability survey on the 80-20 bag in a bag insect resistance management strategy for Bt corn. Quezon City: Biotechnology Coalition of the Philippines (BCP): 2005
50. Brookes G. (2003) The farm level impact of using Bt maize in Spain, ICABR conference paper 2003, Ravello, Italy.
51. Brookes G. The benefits of adopting GM insect resistant (Bt) maize in the EU: first results from 1998-2006. Int J Biotechnol 2008; 134:4-6
52. Gomez-Barbero M, Rodriguez-Cerezo E. (2006) The adoption of GM insect-resistant Bt maize in Spain: an empirical approach, 10th ICABR conference on agricultural biotechnology, Ravello, Italy, July 2006.
53. Riesgo L, et al. 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. Span J Agric Res 2012; 10:867-76; http://dx.doi.org/10.5424/sjar/2012104-448-11
54. Bennett RM, Ismael Y, Kambhampati U, Morse S. Economic impacts of GM cotton in India. AgBioforum 2004; 7:1.
55. IMRB. (2006) Socio-economic benefits of Bollgard and product satisfaction (in India), IMRB International, Mumbai, India.
56. IMRB. (2007) Socio-economic benefits of Bollgard and product satisfaction (in India), IMRB International, Mumbai, India.
57. Herring R, Rao C. On the 'failure of Bt cotton': analysing a decade of experience. Econ Polit Wkly 2012; 157:45-54
58. Zambrano P, Cardona I, Fonseca LA, Magalhaes E, Falck-Zepeda J. (2009) Insect resistant cotton in Columbia: impact on farmers, paper presented to the 13th ICABR conference, Ravello, Italy, June 2009.
59. Vitale J, et al. The economic impact of 2nd generation Bt cotton in West Africa: empirical evidence from Burkina Faso. Int J Biotechnol 2008; 10:167-83; http://dx.doi.org/10.1504/IJBT.2008.018352
60. Vitale J. (2010) 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.
61. Galveo A. Farm survey findings of impact of insect resistant cotton in Brazil, Celeres, Brazil [Internet]. Uberlandia (Brazil): Celeres: c2009-2010 [cited 2 Jan 2014]. Available from: www.celeres.co.br
62. Galveo A. Unpublished (in January 2010) data on first survey findings of impact of insect resistant corn (first crop) in Brazil, Celeres, Brazil [Internet]. Uberlandia (Brazil): Celeres: c2009 [cited 2 Jan 2014]. Available from: www.celeres.co.br
63. Monsanto Brazil (2008) Farm survey of conventional and Bt cotton growers in Brazil 2007, unpublished.
64. Nazli H, Sarker R, Meilke KD, Orden D. (2010) 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.
65. Kouser S, Qaim M. Bt cotton, damage control and optimal levels of pesticide use in Pakistan. Economic Development Economics 2013; 10:179-200.
66. Kouser S, Qaim M. Valuing financial, health and environmental benefits of Bt cotton in Pakistan. Agric Econ 2013; 44:323-35; http://dx.doi.org/10.1111/agec.12014
67. USDA (2011) New technologies aiding Burmese cotton farmers, GAIN report BM 0025 of 14th January 2011.
68. 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.
69. James C (2002) Global review of commercialized transgenic crops 2001: feature Bt cotton, ISAAA No 26.
70. CSIRO. (2005) The cotton consultants Australia 2005 Bollgard II comparison report, CSIRO, Australia.

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71. Fitt G. (2001) 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.
72. Traxler G, Godoy-Avila S, Falck-Zepeda J, Espinoza-Arellano JJ. (2001) Transgenic cotton in Mexico: economic and environmental impacts, ICABR conference, Ravello, Italy.
73. Monsanto Comercial Mexico (2005-2009) Official reports to Mexican Ministry of Agriculture of each year's cotton crop, unpublished.
74. Mullins W, Hudson J. (2004) Bollgard II versus Bollgard sister line economic comparisons, 2004 Beltwide cotton conferences, San Antonio, USA, Jan 2004.

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