
GM crops: global socio-economic and environmental impacts 1996- 2015

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Foreword

This paper is intended for use by a wide range of people with interests in agriculture across the world – farmers, farmer organisations, industry associations, inter-professional bodies, input suppliers, users of agricultural products, government departments, international organisations, non-governmental organisations, politicians, academics, researchers, students and interested citizens.

The material contained in the paper, which is the twelfth annual report on the global economic and environmental impact of genetically modified (GM) crops, aims to provide insights into the reasons why so many farmers around the world have adopted crop biotechnology and continue to use it in their production systems since the technology first became available on a widespread commercial basis in the mid-1990s.

The paper draws, and is largely based on, the considerable body of consistent peer reviewed literature available that has examined the economic and other reasons behind farm level crop biotechnology adoption, together with the environmental impacts associated with the changes¹.

Given the controversy that the use of this technology engenders in some debates and for some people, the work contained in this paper has been submitted and accepted for publication in a peer reviewed publication. The length of this paper, at nearly 200 pages, is too long for acceptance for publication as a single document in peer reviewed journals. Therefore, the authors submitted two papers focusing separately on the economic and environmental impacts of the technology. These papers have been accepted for publication in the peer reviewed journal, GM crops and Food (with open access). The environmental impact paper is available at issue 2017, 8,2, p117-147 <http://dx.doi.org/10.1080/21645698.2017.1309490>. The economic impact paper is forthcoming at 2017, 8, issue 3. These papers follow on from 22 previous peer reviewed papers by the authors on the subject of crop biotechnology impact².

¹ Data from other sources, including industry, is used where no other sources of (representative) data are available. All sources and assumptions used are detailed in the paper

² For example, last year's global impact report covering the years 1996-2014 can be found in the GM Crops journal 2016, 7, 1: 38-77 (economic impacts) and 2016, 7,2: 84-116 (environmental impacts). See also www.pgeconomics.co.uk for a full list of these peer review papers

Executive summary and conclusions

This study presents the findings of research into the global socio-economic and environmental impact of genetically modified (GM) crops in the twenty years since they were first commercially planted on a significant area. It focuses on the farm level economic effects, the production effects, the environmental impact resulting from changes in the use of insecticides and herbicides, and the contribution towards reducing greenhouse gas (GHG) emissions.

Farm income effects³

GM technology has had a significant positive impact on farm income derived from a combination of enhanced productivity and efficiency gains (Table 1). In 2015, the direct global farm income benefit from GM crops was \$15.4 billion. This is equivalent to having added 5.2% to the value of global production of the four main crops of soybeans, maize, canola and cotton. Since 1996, farm incomes have increased by \$167.8 billion.

The largest gains in farm income in 2015 have arisen in the maize sector, largely from yield gains. The \$4.46 billion additional income generated by GM insect resistant (GM IR) maize in 2015 has been equivalent to adding 6.0% to the value of the crop in the GM crop growing countries, or adding the equivalent of 3.2% to the \$138 billion value of the global maize crop in 2015. Cumulatively since 1996, GM IR technology has added \$46 billion to the income of global maize farmers.

Substantial gains have also arisen in the cotton sector through a combination of higher yields and lower costs. In 2015, cotton farm income levels in the GM adopting countries increased by \$3.38 billion and since 1996, the sector has benefited from an additional \$52 billion. The 2015 income gains are equivalent to adding 14% to the value of the cotton crop in these countries, or 9.9% to the \$34 billion value of total global cotton production. This is a substantial increase in value added terms for two new cotton seed technologies.

Significant increases to farm incomes have also resulted in the soybean and canola sectors. The GM HT technology in soybeans has boosted farm incomes by \$3.82 billion in 2015, and since 1996 has delivered \$50 billion of extra farm income. The third year of adoption of 'Intacta' soybeans (combining HT and IR traits) in South America also provided \$1.23 billion of additional farm income and over the three years since 2013 has delivered \$2.4 billion of additional farm income. In the canola sector (largely North American) an additional \$5.48 billion has been generated (1996-2015).

Table 2 summarises farm income impacts in key GM crop adopting countries. This highlights the important farm income benefit arising from GM HT soybeans in South America (Argentina, Bolivia, Brazil, Paraguay and Uruguay), GM IR cotton in China and India and a range of GM cultivars in the US. It also illustrates the growing level of farm income benefits being obtained in South Africa, the Philippines, Mexico and Colombia.

In terms of the division of the economic benefits obtained by farmers in developing countries relative to farmers in developed countries, Table 3 shows that in 2015, 48.7% of the farm income benefits have been earned by developing country farmers. The vast majority of these income

³ See section 3 for details

gains for developing country farmers have been from GM IR cotton and GM HT soybeans⁴. Over the twenty years, 1996-2015, the cumulative farm income gain derived by developing country farmers was 51.3% (\$86.1 billion).

Examining the cost farmers pay for accessing GM technology, Table 4 shows that across the four main GM crops, the total cost in 2015 was equal to 29% of the total technology gains (inclusive of farm income gains plus cost of the technology payable to the seed supply chain⁵).

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

Table 1: Global farm income benefits from growing GM crops 1996-2015: million US \$

Trait	Increase in farm income 2015	Increase in farm income 1996-2015	Farm income benefit in 2015 as % of total value of production of these crops in GM adopting countries	Farm income benefit in 2015 as % of total value of global production of crop
GM herbicide tolerant soybeans	3,821.7	50,039.7	4.3	4.2
GM herbicide tolerant and insect resistant soybeans	1,226.8	2,405.2	2.4	0.69
GM herbicide tolerant maize	1,787.9	11,103.8	2.4	1.0
GM herbicide tolerant cotton	116.7	1,772.7	0.5	0.3
GM herbicide tolerant canola	655.0	5,479.6	8.1	2.4
GM insect resistant maize	4,464.0	45,958.1	6.0	3.2
GM insect resistant cotton	3,266.6	50,274.8	13.5	9.6
Others	65.8	717.3	Not applicable	Not applicable
Totals	15,404.5	167,751.2	5.2	7.9

Notes: All values are nominal. Others = Virus resistant papaya and squash and herbicide tolerant sugar beet. Totals for the value shares exclude 'other crops' (ie, relate to the 4 main crops of soybeans, maize, canola and cotton). Farm income calculations are net farm income changes after inclusion of impacts on

⁴ The authors acknowledge that the classification of different countries into developing or developed country status affects the distribution of benefits between these two categories of country. The definition used in this paper is consistent with the definition used by James (2014)

⁵ 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

yield, crop quality and key variable costs of production (eg, payment of seed premia, impact on crop protection expenditure)

Table 2: GM crop farm income benefits 1996-2015 selected countries: million US \$

	GM HT soybeans	GM HT maize	GM HT cotton	GM HT canola	GM IR maize	GM IR cotton	GM HT/IR soybeans	Total
US	23,133.7	7,237.9	1,098.8	339.6	35,423.5	5,022.0	N/a	72,255.5
Argentina	17,367.8	1,696.2	161.9	N/a	946.7	868.8	80.9	21,122.3
Brazil	6,700.8	1,777.0	153.5	N/a	5,392.9	100.6	2,264.9	16,389.7
Paraguay	1,125.5	2.5	N/a	N/a	22.9	N/a	35.3	1,186.2
Canada	755.6	161.6	N/a	5,066.1	1,345.0	N/a	N/a	7,328.3
South Africa	22.2	65.6	4.4	N/a	1,925.5	32.1	N/a	2,049.8
China	N/a	N/a	N/a	N/a	N/a	18,654.4	N/a	18,654.4
India	N/a	N/a	N/a	N/a	N/a	19,598.7	N/a	19,598.7
Australia	N/a	N/a	99.1	74.0	N/a	849.9	N/a	1,023.0
Mexico	6.0	N/a	230.7	N/a	N/a	252.3	N/a	489.0
Philippines	N/a	156.6	N/a	N/a	485.1	N/a	N/a	641.7
Romania	44.6	N/a	N/a	N/a	N/a	N/a	N/a	44.6
Uruguay	161.4	1.9	N/a	N/a	28.1	N/a	24.2	215.6
Spain	N/a	N/a	N/a	N/a	251.3	N/a	N/a	251.3
Other EU	N/a	N/a	N/a	N/a	23.6	N/a	N/a	23.6
Colombia	N/a	4.5	24.3	N/a	103.4	20.8	N/a	153.0
Bolivia	722.0	N/a	N/a	N/a	N/a	N/a	N/a	722.0
Myanmar	N/a	N/a	N/a	N/a	N/a	307.9	N/a	307.9
Pakistan	N/a	N/a	N/a	N/a	N/a	4,311.6	N/a	4,311.6
Burkina Faso	N/a	N/a	N/a	N/a	N/a	204.6	N/a	204.6
Honduras	N/a	N/a	N/a	N/a	10.3	N/a	N/a	10.3

Notes: All values are nominal. Farm income calculations are net farm income changes after inclusion of impacts on yield, crop quality and key variable costs of production (eg, payment of seed premia, impact on crop protection expenditure). N/a = not applicable. US total figure also includes \$706.8 million for other crops/traits (not included in the table). Also, not included in the table is \$10.5 million extra farm income from GM HT sugar beet in Canada

Table 3: GM crop farm income benefits 2015: developing versus developed countries: million US \$

	Developed	Developing
GM HT soybeans	2,301.1	1,520.6
GM HT & IR soybeans	0	1,226.8
GM HT maize	1,156.1	631.8
GM HT cotton	32.3	84.4
GM HT canola	655.0	0
GM IR maize	3,372.7	1,091.3
GM IR cotton	320.0	2,946.6
GM virus resistant papaya and squash and GM HT sugar beet	65.8	0
Total	7,903.0	7,501.5

Developing countries = all countries in South America, Mexico, Honduras, Burkina Faso, India, China, Pakistan, Myanmar, the Philippines and South Africa

Table 4: Cost of accessing GM technology (million \$) relative to the total farm income benefits 2015

	Cost of technology : all farmers	Farm income gain: all farmers	Total benefit of technology to farmers and seed supply chain	Cost of technology: developing countries	Farm income gain: developing countries	Total benefit of technology to farmers and seed supply chain: developing countries
GM HT soybeans	1,990.3	3,821.7	5,812.0	204.6	1,520.6	1,725.2
GM HT & IR soybeans	411.9	1,226.8	1,638.7	411.9	1,226.8	1,638.7
GM HT maize	1,051.3	1,787.9	2,839.2	177.9	631.8	809.7
GM HT cotton	252.2	116.7	368.9	25.5	84.4	109.9
GM HT canola	104.3	655.0	759.3	0	0	0
GM IR maize	1,858.5	4,464.0	6,322.5	626.0	1,091.3	1,717.3
GM IR cotton	567.1	3,266.6	3,833.7	376.9	2,946.6	3,323.5
Others	70.4	65.8	136.2	0	0	0
Total	6,306.0	15,404.5	21,710.5	1,822.8	7,501.5	9,324.3

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

Production effects of the technology

Based on the yield impacts used in the direct farm income benefit calculations (see appendix 2) 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 5).

The GM IR traits, used in maize and cotton, have accounted for 94.7% 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 20 years since 1996 has been +13.1% for maize and +15% for cotton.

The primary impacts of GM HT technology have been to provide more cost effective (less expensive) and easier weed control. In some countries, the improved weed control has led to higher yields, though the main source of additional production has been via the facilitation of no tillage production systems and how this has shortened the production cycle and 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 148 million tonnes to soybean production in Argentina and Paraguay between 1996 and 2015 (accounting for 84.9% of the total GM HT-related additional soybean production). Intacta (IR) soybeans have also added a further 5.84 million tonnes to global soybean production.

Table 5: Additional crop production arising from positive yield effects of GM crops

	1996-2015 additional production (million tonnes)	2015 additional production (million tonnes)
Soybeans	180.3	21.90
Corn	357.7	40.30
Cotton	25.2	2.19
Canola	10.6	1.44
Sugar beet	1.1	0.15

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

Environmental impact from changes in insecticide and herbicide use⁶

To examine this impact, the study has analysed both active ingredient use and utilised the indicator known as the Environmental Impact Quotient (EIQ) to assess the broader impact on the environment (plus impact on animal and human health). The EIQ distils the various environmental and health impacts of individual pesticides in different GM and conventional production systems into a single 'field value per hectare' and draws on key toxicity and environmental exposure data related to individual products. It therefore provides a better measure to contrast and compare the impact of various pesticides on the environment and human health than weight of active ingredient alone. Readers should, however, note that the EIQ is an indicator only (primarily of toxicity) and does not take into account all environmental issues and impacts. In the analysis of GM HT production, we have assumed that the conventional alternative delivers the same level of weed control as occurs in the GM HT production system.

GM traits have contributed to a significant reduction in the environmental impact associated with insecticide and herbicide use on the areas devoted to GM crops (Table 6). Since 1996, the use of pesticides on the GM crop area was reduced by 618.7 million kg of active ingredient (8.1% reduction), and the environmental impact associated with herbicide and insecticide use on these crops, as measured by the EIQ indicator, fell by 18.6%.

In absolute terms, the largest environmental gain has been associated with the adoption of GM insect resistant (IR) technology. GM IR cotton has contributed a 43% reduction in the total volume of active ingredient used on GM crops (-268.7 million kg active ingredient, equivalent to a 29.1% reduction in insecticide use on the GM IR cotton area) and a 31.5% reduction in the total field EIQ indicator measure associated with GM crop use (1996-2015) due to the significant reduction in insecticide use that the technology has facilitated, in what has traditionally been an intensive user of insecticides. Similarly, the use of GM IR technology in maize has led to

⁶ See section 4.1

important reductions in insecticide use (87.1 million kg of active ingredient), with associated environmental benefits.

The volume of herbicides used in GM maize crops also decreased by 226.3 million kg (1996-2015), an 8.4% reduction, whilst the overall environmental impact associated with herbicide use on these crops decreased by a significantly larger 12.7%. This highlights the switch in herbicides used with most GM herbicide tolerant (HT) crops to active ingredients with a more environmentally benign profile than the ones generally used on conventional crops.

Important environmental gains have also arisen in the soybean and canola sectors. In the soybean sector, whilst herbicide use increased by 15.3 million kg (+0.5%: 1996-2015), the associated environmental impact of herbicide use on this crop area decreased (improved) by 13.9%, due to a switch to more environmentally benign herbicides. In the canola sector, farmers reduced herbicide use by 25 million kg (an 18.1% reduction) and the associated environmental impact of herbicide use on this crop area fell by 29.9% (due to a switch to more environmentally benign herbicides).

In terms of the division of the environmental benefits associated with less insecticide and herbicide use for farmers in developed countries relative to farmers in developing countries, Table 7 shows a 51%:49% split of the environmental benefits (1996-2015) respectively in developed (51%) and developing countries (49%). Sixty-eight per cent of the environmental gains in developing countries have been from the use of GM IR cotton.

Table 6: Impact of changes in the use of herbicides and insecticides from growing GM crops globally 1996-2015

Trait	Change in volume of active ingredient used (million kg)	Change in field EIQ impact (in terms of million field EIQ/ha units)	% change in ai use on GM crops	% change in environmental impact associated with herbicide & insecticide use on GM crops	Area GM trait 2015 (million ha)
GM herbicide tolerant soybeans	+15.3	-8,112	+0.5	-13.9	76.7
GM herbicide tolerant & insect resistant soybeans	-3.6	-348	-1.4	-4.3	22.3
GM herbicide tolerant maize	-226.3	-7,315	-8.4	-12.7	45.3
GM herbicide tolerant canola	-25.0	-854	-18.1	-29.9	8.6
GM herbicide tolerant cotton	-25.1	-629	-7.6	-10.2	4.2
GM insect resistant maize	-87.1	-3,891	-53.3	-57.7	46.1
GM insect resistant cotton	-268.7	-11,949	-29.1	-31.5	21.5

GM herbicide tolerant sugar beet	+1.8	-1.3	+24.9	-0.9	0.47
Totals	-618.7	-33,100	-8.1	-18.6	

Table 7: GM crop environmental benefits from lower insecticide and herbicide use 1996-2015: developing versus developed countries

	Change in field EIQ impact (in terms of million field EIQ/ha units): developed countries	Change in field EIQ impact (in terms of million field EIQ/ha units): developing countries
GM HT soybeans	-5,530.4	-2,582.1
GM HT & IR soybeans	0	-348.5
GM HT maize	-6,405.9	-909.2
GM HT cotton	-510.1	-118.9
GM HT canola	-853.9	0
GM IR maize	-2,743.2	-1,148.0
GM IR cotton	-994.5	-10,954.3
GM HT sugar beet	-1.3	0
Total	-17,039.3	-16,061.0

It should, however, be noted that in some regions where GM HT crops have been widely grown, some farmers have relied too much on the use of glyphosate to manage weeds in GM HT crops and this has contributed to the development of weed resistance. There are currently 36 weeds recognised as exhibiting resistance to glyphosate worldwide, of which several are not associated with glyphosate tolerant crops (www.weedscience.org). For example, there are currently 16 weeds recognised in the US as exhibiting resistance to glyphosate, of which two are not associated with glyphosate tolerant crops. In the US, the affected area is currently within a range of 40%-60% of the total area annually devoted to maize, cotton, canola, soybeans and sugar beet (the crops in which GM HT technology is used).

In recent years, there has also been a growing consensus among weed scientists of a need for changes in the weed management programmes in GM HT crops, because of the evolution of these weeds towards populations that are resistant to glyphosate. 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 integrated weed management systems, even where instances of weed resistance to glyphosate have not been found.

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

At the macro level, the adoption of more integrated weed management strategies in GM HT crops has influenced the mix, total amount and overall environmental profile of herbicides applied to GM HT soybeans, cotton, maize and canola in the last 10 years and this is reflected in the data presented in this paper.

Impact on greenhouse gas (GHG) emissions⁷

The scope for GM crops contributing to lower levels of GHG emissions comes from two principal sources:

- Reduced fuel use from less frequent herbicide or insecticide applications and a reduction in the energy use in soil cultivation. The fuel savings associated with making fewer spray runs (relative to conventional crops) and the switch to conservation, reduced and no-till farming systems, have resulted in permanent savings in carbon dioxide emissions. In 2015, this amounted to about 2,819 million kg (arising from reduced fuel use of 1,056 million litres). Over the period 1996 to 2015 the cumulative permanent reduction in fuel use is estimated at 26,223 million kg of carbon dioxide (arising from reduced fuel use of 9,821 million litres);
- The use of 'no-till' and 'reduced-till'⁸ farming systems. These production systems have increased significantly with the adoption of GM HT crops because the GM HT technology has improved farmers' ability to control competing weeds, reducing the need to rely on soil cultivation and seed-bed preparation as means to getting good levels of weed control. As a result, tractor fuel use for tillage is reduced, soil quality is enhanced and levels of soil erosion cut. In turn more carbon remains in the soil and this leads to lower GHG emissions. Based on savings arising from the rapid adoption of no till/reduced tillage farming systems in North and South America, an extra 5,738 million kg of soil carbon is estimated to have been sequestered in 2015 (equivalent to 21,060 million kg of carbon dioxide that has not been released into the global atmosphere). Cumulatively, the amount of carbon sequestered is likely to be higher due to year-on-year benefits to soil quality; however, it is equally likely that the total cumulative soil sequestration gains are not the sum of each individual year's estimated saving because only a proportion of the crop area will have remained in permanent no-till and reduced tillage. It is not possible to confidently estimate cumulative soil sequestration gains that take into account reversions to conventional tillage because of a lack of data. Consequently, our estimate of 227,208 million kg of carbon dioxide not released into the atmosphere for the cumulative period 1996-2015 should be treated with caution.

Placing these carbon sequestration benefits within the context of the carbon emissions from cars, Table 8 shows that:

- In 2015, the permanent carbon dioxide savings from reduced fuel use were the equivalent of removing 1.25 million cars from the road;
- The additional probable soil carbon sequestration gains in 2015 were equivalent to removing 10.62 million cars from the roads;
- In total, in 2015, the combined GM crop-related carbon dioxide emission savings from reduced fuel use and additional soil carbon sequestration were equal to the removal from the roads of 11.88 million cars, equivalent to 41% of all registered cars in the UK;
- It is not possible to confidently estimate the probable soil carbon sequestration gains since 1996. If the entire GM HT crop in reduced or no tillage agriculture during the last twenty years had remained in permanent reduced/no tillage then this would have

⁷ See section 4.2

⁸ No-till farming means that ground is hardly disturbed at planting (not ploughed), while reduced tillage means that ground is disturbed less than it would be with traditional tillage systems. For example, under a no-till farming system, soybean seeds are planted through the organic material that is left over from a previous crop such as corn, cotton or wheat

resulted in a carbon dioxide saving of 227,208 million kg, equivalent to taking 101 million cars off the road. This is, however, a maximum possibility and the actual levels of carbon dioxide reduction are likely to be lower.

Table 8: Context of carbon sequestration impact 2015: car equivalents

Crop/trait/country	Permanent carbon dioxide savings arising from reduced fuel use (million kg of carbon dioxide)	Permanent fuel savings: as average family car equivalents removed from the road for a year ('000s)	Potential additional soil carbon sequestration savings (million kg of carbon dioxide)	Soil carbon sequestration savings: as average family car equivalents removed from the road for a year ('000s)
HT soybeans				
Argentina	739	329	7,496	3,332
Brazil	501	223	5,082	2,259
Bolivia, Paraguay, Uruguay	170	75	1,722	765
US	528	235	2,840	1,262
Canada	47	21	247	110
HT maize				
US	387	172	5,495	2,442
Canada	19	8	54	24
HT canola				
Canada	191	85	964	428
IR maize				
Brazil	83	37	0	0
USA, Canada, South.Africa, Spain	11	5	0	0
IR cotton				
Global	35	16	0	0
IR soybeans				
S.America	108	48	0	0
Total	2,819	1,254	23,900	10,622

Notes:

1. Assumption: an average family car produces 150 grams of carbon dioxide per km. A car does an average of 15,000 km/year and therefore produces 2,250 kg of carbon dioxide/year
2. IR soybeans = savings from reduced insecticide use. All other savings associated with the HT stack in 'Intacta' soybeans included under HT soybeans

1 Introduction

This study⁹ examines the socio-economic impact on farm income and environmental impacts arising from pesticide usage and greenhouse gas (GHG) emissions, of crop biotechnology, over the twenty-year period 1996-2015¹⁰. It also quantifies the production impact of the technology on the key crops where it has been used.

1.1 Objectives

The principal objective of the study was to identify the global socio-economic and environmental impact of genetically modified (GM) crops over the first twenty years of widespread commercial production.

More specifically, the report examines the following impacts:

Socio-economic impacts on:

- Cropping systems: risks of crop losses, use of inputs, crop yields and rotations;
- Farm profitability: costs of production, revenue and gross margin profitability;
- Indirect (non pecuniary) impacts of the technology;
- Production effects;
- Trade flows: developments of imports and exports and prices;
- Drivers for adoption such as farm type and structure

Environmental impacts on:

- Insecticide and herbicide use, including conversion to an environmental impact measure¹¹;
- Greenhouse gas (GHG) emissions.

1.2 Methodology

The report has been compiled based largely on desk research and analysis. A detailed literature review¹² has been undertaken to identify relevant data. Primary data for impacts of commercial cultivation were not available for every crop, in every year and for each country, but all representative, previous research has been utilised. The findings of this research have been used as the basis for the analysis presented¹³, although where relevant, we have undertaken primary analysis from base data (eg, calculation of the environmental impacts). More specific information about assumptions used and their origins are provided in each of the sections of the report.

⁹ 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

¹⁰ This study updates earlier studies produced in 2005, 2006, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015 and 2016, covering the first nine, ten, eleven, twelve, thirteen, fourteen, fifteen, sixteen, seventeen, eighteen and nineteen years of GM crop adoption globally. Readers should, however, note that some data presented in this report are not directly comparable with data presented in the earlier papers because the current paper takes into account the availability of new data and analysis (including revisions to data applicable to earlier years)

¹¹ The Environmental Impact Quotient (EIQ), based on Kovach J et al (1992 & annually updated) – see references

¹² See References

¹³ Where several pieces of research of relevance to one subject (eg, the impact of using a biotech trait on the yield of a crop) have been identified, the findings used have been largely based on the average

1.3 Structure of report

The report is structured as follows:

- Section one: introduction;
- Section two: overview of biotech crop plantings by trait and country;
- Section three: farm level profitability impacts by trait and country, intangible (non pecuniary) benefits, structure and size, prices, production impact and trade flows;
- Section four: environmental impacts covering impact of changes in herbicide and insecticide use and contributions to reducing GHG emissions.

2 Global context of GM crops

This section provides a broad overview of the global development of GM crops over the twenty-year period 1996-2015.

2.1 Global plantings

Although the first commercial GM crops were planted in 1994 (tomatoes), 1996 was the first year in which a significant area of crops containing GM traits were planted (1.66 million hectares). Since then there has been a dramatic increase in plantings and by 2015, the global planted area was 171.5 million hectares.

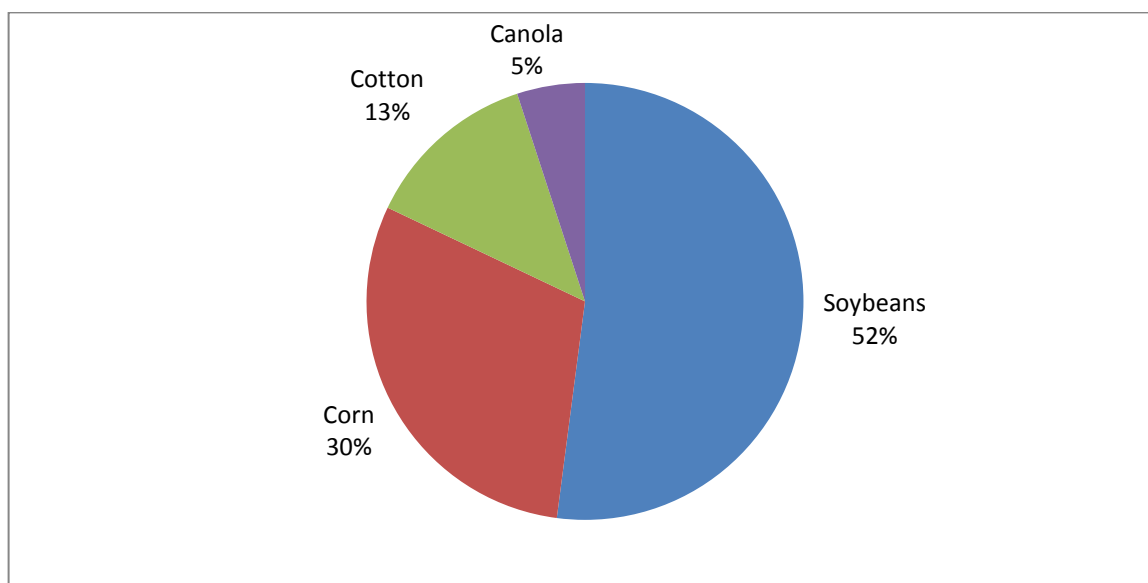
In terms of the share of the main crops in which GM traits have been commercialised (soybeans, maize/corn, cotton and canola), GM traits accounted for 48% of the global plantings to these four crops in 2015.

2.2 Plantings by crop and trait

2.2.1 By crop

Almost all of the global GM crop area derives from soybeans, maize/corn, cotton and canola (Figure 1)¹⁴. In 2015, GM soybeans accounted for the largest share (52%), followed by corn (30%), cotton (13%) and canola (5%).

Figure 1: GM crop plantings 2015 by crop (base area of the four GM crops: 171.5 million hectares (ha))

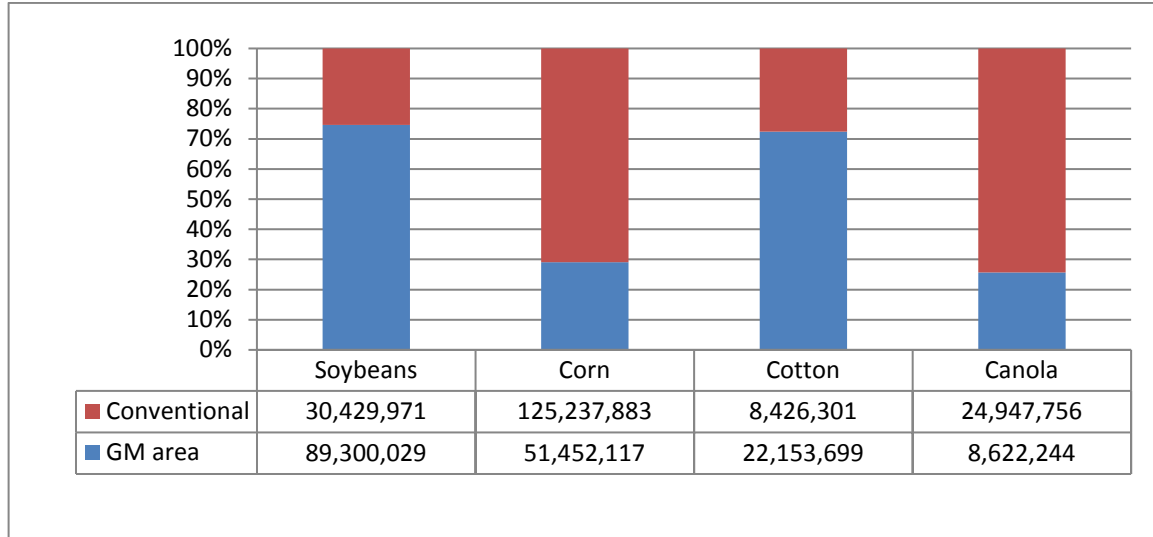


Sources: Various including ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio, National Ministries of Agriculture (Mexico, Philippines, Spain), Grains South Africa

¹⁴ In 2015 there were also additional GM crop plantings of papaya (455 hectares), squash (1,000 hectares), sugar beet (454,000 ha) and alfalfa (about 1.3 million ha) in the US. There were also 5,000 hectares of papaya in China, 15,000 of sugar beet in Canada and 25 ha of insect resistant brinjal in Bangladesh

In terms of the share of total global plantings to these four crops, GM traits accounted for the majority of soybean plantings (75%) in 2015. For the other three main crops, the GM shares were 29% for maize/corn, 72% for cotton and 26% for canola (Figure 2).

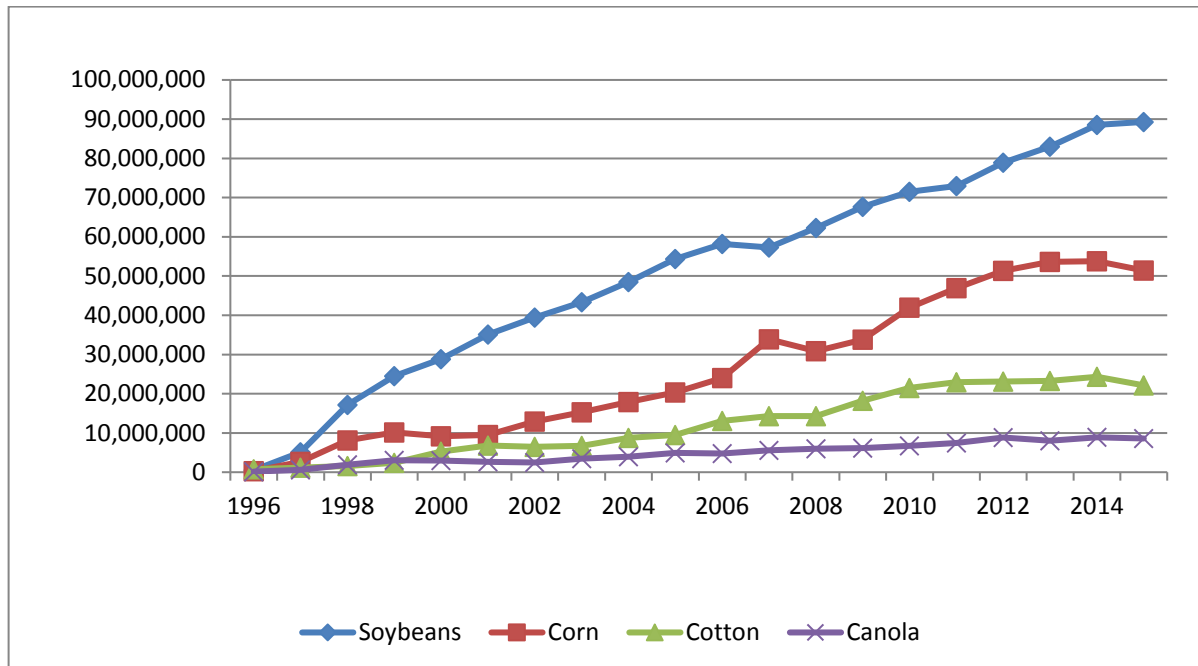
Figure 2: 2015: share of GM crops in global plantings of key crops (ha)



Sources: Various including ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio, National Ministries of Agriculture (Mexico, Philippines, Spain), Grains South Africa

The trend in plantings to GM crops (by crop) since 1996 is shown in Figure 3.

Figure 3: Global GM crop plantings by crop 1996-2015 (ha)

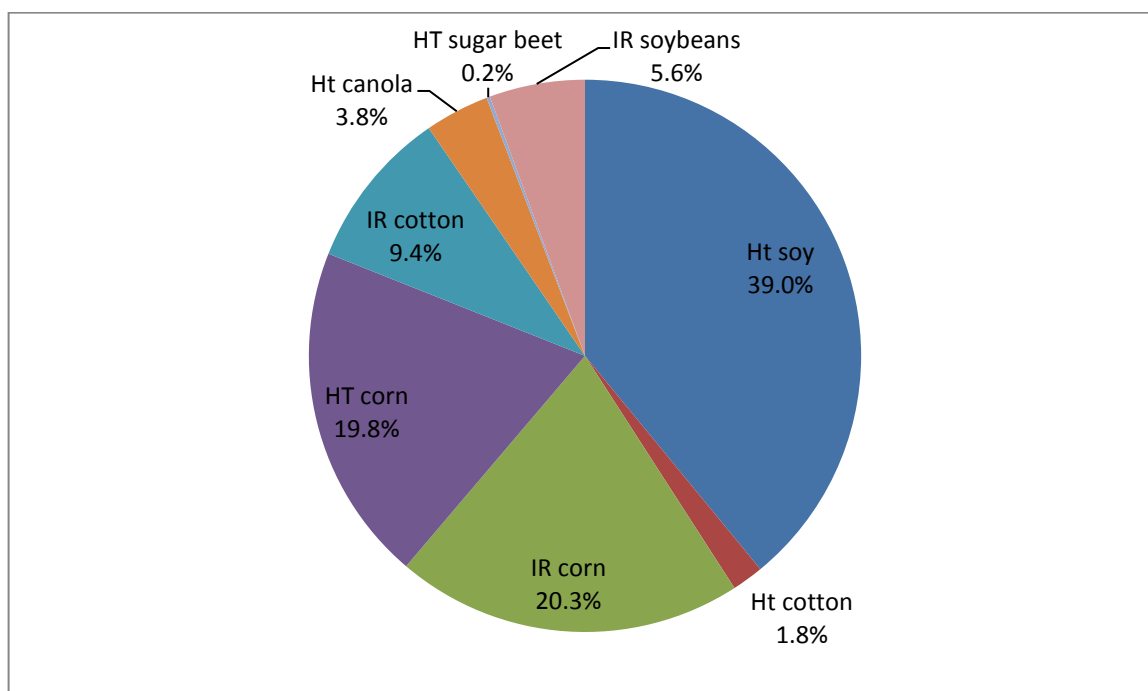


Sources: Various including ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio, National Ministries of Agriculture (Mexico, Philippines, Spain), Grains South Africa

2.2.2 By trait

Figure 4 summarises the breakdown of the main GM traits planted globally in 2015. GM herbicide tolerant (HT) soybeans dominate, accounting for 39% of the total, followed by insect resistant (IR: largely Bt) maize, HT maize and IR cotton with respective shares of 20%, 20% and 9%¹⁵. In total, HT crops account for 65%, and insect resistant crops account for 35% of global plantings.

Figure 4: Global GM crop plantings by main trait and crop: 2015

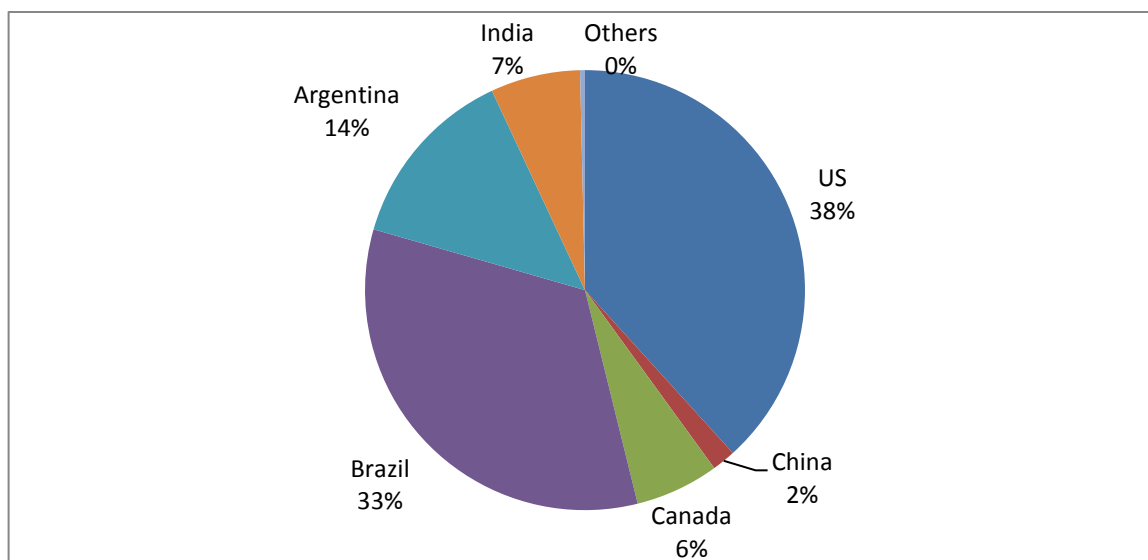


Sources: Various including ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio, National Ministries of Agriculture (Mexico, Philippines, Spain), Grains South Africa

2.2.3 By country

The US had the largest share of global GM crop plantings in 2015 (38%), followed by Brazil (33%). The other main countries planting GM crops in 2015 were Argentina, India, Canada and China (Figure 5).

¹⁵ The reader should note that the total plantings by trait produces a higher global planted area (228.7 million ha) than the global area by crop (171.5 million ha) because of the planting of some crops containing the stacked traits of herbicide tolerance and insect resistance

Figure 5: Global GM crop plantings 2015 by country

Sources: Various including ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio, National Ministries of Agriculture (Mexico, Philippines, Spain), Grains South Africa

In terms of the GM share of production in the main adopting countries, Table 9 shows that, in 2015, the technology accounted for important shares of total production of the four main crops, in several countries. More specifically:

- *US*: was one of the first countries to adopt the technology in 1996 for traits in soybeans, maize and cotton, and from 1999 in canola, hence the very high adoption levels that have been reached in 2015. Almost all of the US sugar beet crop (98%) also used GM HT technology in 2015;
- *Canada and Argentina*: like the US were early adopters, with the technology now dominating production in the three crops of soybeans, maize and canola in Canada, and maize, cotton and soybeans in Argentina;
- *South Africa*: was the first, and remains the primary African country¹⁶ to embrace the technology, which was first used commercially in 2000. The technology is widely used in the important crops of maize and soybeans, and now accounts for all of the small cotton crop (9,100 ha in 2015);
- *Australia*: was an early adopter of GM technology in cotton (1996), with GM traits now accounting for almost all cotton production. Extension of the technology to other crops did, however, not occur until 2008 when HT canola was allowed in some Australian states;
- In *Asia*, seven countries used GM crops in 2015. China was the first Asian country to use the technology commercially back in 1997 when GM IR technology was first used. This technology rapidly expanded to about two thirds of the total crop within five years and accounted for 96% of the crop in 2015. GM virus resistant papaya has also been used in China since 2008. In India, IR cotton was first adopted in 2002, and its use

¹⁶ The only other African countries where commercial GM crops grew in 2015 were Burkina Faso (first used commercially in 2008, IR cotton accounted for 50% (330,000 ha) of the total crop) and Sudan, first grown commercially in 2012 and where GM IR cotton was planted on 47,500 ha in 2015

increased rapidly in subsequent years, so that by 2015 this technology dominates total cotton production (95% of the total). IR cotton is also grown in Pakistan and Myanmar. In the Philippines, IR maize was first used commercially in 2003, with HT maize also adopted from 2006. Lastly, Vietnam adopted IR/HT maize in 2015;

- In *South America*, there are interesting country examples where the adoption of GM technology in one country resulted in a spread of the technology, initially illegally, across borders into countries which were first reluctant to legalise the use of the technology. Thus GM HT soybeans were first grown illegally in the southernmost states of Brazil in 1997, a year after legal adoption in Argentina. It was not until 2003 that the Brazilian government legalised the commercial growing of GM HT soybeans, when more than 10% of the country's soybean crop had been using the technology illegally (in 2002). Since then, GM technology use has extended to cotton in 2006 and maize in 2008. A similar process of widespread illegal adoption of GM HT soybeans occurred in Paraguay and Bolivia before the respective governments authorised the planting of soybean crops using this GM trait. Intacta soybeans (insect resistant and herbicide tolerant) were also adopted in Brazil, Paraguay, Argentina and Uruguay from 2013.

Table 9: GM share of crop plantings in 2015 by country (% of total plantings)

	Soybeans	Maize	Cotton	Canola
USA	94	93	94	93
Canada	85	87	N/a	93
Argentina	99	83	100	N/a
South Africa	95	90	100	N/a
Australia	N/a	N/a	100	20
China	N/a	N/a	96	N/a
Philippines	N/a	27	N/a	N/a
Paraguay	94	42	100	N/a
Brazil	94	85	73	N/a
Uruguay	100	88	N/a	N/a
India	N/a	N/a	95	N/a
Colombia	N/a	15	80	N/a
Mexico	7	N/a	96	N/a
Bolivia	80	N/a	N/a	N/a
Burkina Faso	N/a	N/a	50	N/a
Pakistan	N/a	N/a	93	N/a
Myanmar	N/a	N/a	93	N/a

Note: N/a = not applicable

3 The farm level economic impact of GM crops 1996-2015

This section examines the farm level economic impact of growing GM crops and covers the following main issues:

- Impact on crop yields;
- Effect on key costs of production, notably seed cost and crop protection expenditure;
- Impact on other costs such as fuel and labour;
- Effect on profitability;
- Other impacts such as crop quality, scope for planting a second crop in a season and impacts that are often referred to as intangible impacts such as convenience, risk management and husbandry flexibility;
- Production effects.

The analysis is based on an extensive examination of existing farm level impact data for GM crops. 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.

As the economic performance and impact of this technology at the farm level varies widely, both between and within regions/countries (as applies to any technology used in agriculture), the measurement of performance and impact is considered on a case by case basis in terms of crop and trait combinations. The analysis presented is based on the average performance and impact recorded in different crops by the studies reviewed; the average performance being the most common way in which the identified literature has reported impact. Where several pieces 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) have been identified, the findings used have been largely based on the average of these findings.

This approach may overstate or understate the real 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 is not available, the authors have had to extrapolate available impact data from identified studies for years for which no data are available. It is acknowledged that this represents a potential methodological weakness of the research. To reduce the possibilities of over/understating impact, 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 years¹⁷. 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 as identified by research;
- Uses current farm level crop prices and bases any yield impacts on (adjusted – see below) current average yields. In this way some degree of dynamic has been introduced into the

¹⁷ Examples where such data is available include the impact of GM (IR cotton: in India (see Bennett et al (2004), IMRB (2006) and IMRB (2007)), in Mexico (see Traxler et al (2001) and Monsanto Mexico (annual reports to the Mexican government)) and in the US (see Sankala & Blumenthal (2003 and 2006), Mullins & Hudson (2004))

- analysis that would, otherwise, be missing if constant prices and average yields identified in year-specific studies had been used;
- Includes some changes and updates to the impact assumptions identified in the literature based on consultation with local sources (analysts, industry representatives) so as to better reflect prevailing/changing conditions (eg, pest and weed pressure, cost of technology);
 - 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 (see Appendix 1 for examples).

Appendix 2 also provides details of the impacts, assumptions applied and sources.

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

- Impact is quantified at the trait and crop level, including where stacked traits are available to farmers. Where stacked traits have been used, the individual trait components were analysed separately to ensure estimates of all traits were calculated;
- 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;
- 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 labour¹⁸), 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 herbicide tolerant (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 biotech crop adoption on global crop supply and world prices.

The section also examines some of the more intangible (more difficult to quantify) economic impacts of GM technology. The literature in this area is much more limited and in terms of aiming to quantify these impacts, largely restricted to the US-specific studies. The findings of this research are summarised¹⁹ and extrapolated to the cumulative biotech crop planted areas in the US over the period 1996-2015.

¹⁸ Where available – information and analysis on these costs is 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 most cases the analysis relates to impact of crop protection and seed cost only

¹⁹ Notably relating to the US - Marra and Piggott (2006)

Lastly, the paper 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 (where identified), but also from the facilitation of additional cropping within a season (notably in relation to soybeans in South America).

The section is structured on a trait and country basis highlighting the key farm level impacts.

3.1 Herbicide tolerant soybeans

3.1.1 The US

First generation GM HT soybeans

In 2015, 94% (31.1 million ha) of the total US soybean crop was planted to GM HT cultivars. Of this, 10.2 million ha were first generation GM HT soybeans. The farm level impact of using this technology since 1996 is summarised in Table 10.

The key features are as follows:

- The primary impact has been to reduce the cost of production. In the early years of adoption these savings were between \$25/ha and \$34/ha. In more recent years, estimates of the cost savings have been in the range of \$30/ha and \$85/ha (based on a comparison of conventional herbicide regimes that are required to deliver a comparable level of weed control to the GM HT soybean system). In the period between 2008 and 2010, the cost savings declined relative to earlier years, mainly because of the significant increase in the global price of glyphosate relative to increases in the price of other herbicides (commonly used on conventional soybeans). In addition, growers of GM HT soybean crops are increasingly faced with the problem of weed species becoming resistant to glyphosate. This has resulted in the need to include use of other herbicides (with different and complementary modes of action) in combination with glyphosate to address the weed resistance (to glyphosate) issues (see section 4 for more detailed discussion of this issue). At the macro level, these changes have influenced the mix, volume; cost and overall profile of herbicides applied to GM HT soybeans in the last 10 years, and is shown here by the annually changing levels of cost savings associated with the adoption of GM HT technology. Overall, the main benefit of the technology has been cost savings associated with lower herbicide costs²⁰ plus a saving in labour and machinery costs of between about \$6/ha and \$10/ha;
- Against the background of underlying improvements in average yield levels over the 1996-2015 period (via improvements in plant breeding, including the adoption of second generation HT soybeans – see below), the specific yield impact of the first generation of GM HT technology used up to 2015 has been neutral²¹;

²⁰ Whilst there were initial cost savings in herbicide expenditure, these increased when glyphosate came off-patent in 2000. Growers of GM HT soybeans initially applied Monsanto's Roundup herbicide but over time, and with the availability of low cost generic glyphosate alternatives, many growers switched to using these generic alternatives (the price of Roundup also fell significantly post 2000)

²¹ Some early studies of the impact of GM HT soybeans in the US suggested that GM HT soybeans produced lower yields than conventional soybean varieties. Where this may have occurred it applied only in early years of adoption, when the technology was not present in all leading varieties suitable for all of the main growing regions of the USA. By 1998/99 the technology was available in leading varieties and no statistically significant average yield differences have been found between GM (first generation) and conventional soybean varieties

- The annual total national farm income benefit from using the technology rose from \$5 million in 1996 to \$1.42 billion in 2007. Since then the aggregate farm income gains have fluctuated, with the 2015 gain being \$202.6 million. The cumulative farm income benefit over the 1996-2015 period (in nominal terms) was \$13.14 billion.

Table 10: Farm level income impact of using GM HT soybeans (first generation) in the US 1996-2015

Year	Cost savings (\$/ha)	Net cost saving/increase in gross margins, inclusive of cost of technology (\$/ha)	Increase in farm income at a national level (\$ millions)
1996	25.2	10.39	5.0
1997	25.2	10.39	33.2
1998	33.9	19.03	224.1
1999	33.9	19.03	311.9
2000	33.9	19.03	346.6
2001	73.4	58.56	1,298.5
2002	73.4	58.56	1,421.7
2003	78.5	61.19	1,574.9
2004	60.1	40.33	1,096.8
2005	69.4	44.71	1,201.4
2006	57.0	32.25	877.1
2007	85.2	60.48	1,417.2
2008	57.1	32.37	899.5
2009	54.7	15.90	437.2
2010	66.2	28.29	761.9
2011	67.1	14.60	312.0
2012	71.3	25.62	402.7
2013	62.7	13.30	148.3
2014	59.8	15.91	165.1
2015	68.3	19.29	202.6

Sources and notes:

1. Impact data 1996-1997 based on Marra et al (2002), 1998-2000 based on Carpenter and Gianessi (1999) and 2001 onwards based on Sankala & Blumenthal (2003 & 2006), Johnson and Strom (2008) plus updated 2008 onwards to reflect recent changes in herbicide prices and weed control programmes
2. Cost of technology: \$14.82/ha 1996-2002, \$17.3/ha 2003, \$19.77/ha 2004, \$24.71/ha 2005-2008, \$38.79/ha 2009, \$37.95/ha 2010, \$52.53/ha 2011, \$45.71/ha 2012, \$49.42/ha 2013, \$43.93 in 2014, \$48.97 2015
3. The higher values for the cost savings in 2001 onwards reflect the methodology used by Sankala & Blumenthal, which was to examine the conventional herbicide regime that would be required to deliver the same level of weed control in a low/reduced till system to that delivered from the GM HT no/reduced till soybean system. This is a more robust methodology than some of the more simplistic alternatives used elsewhere. In earlier years the cost savings were based on comparisons between GM HT soy growers and/or conventional herbicide regimes that were commonplace prior to commercialisation in the mid 1990s when conventional tillage systems were more important

Second generation GM HT soybeans

A second generation of GM HT soybeans became available to commercial soybean growers in the US in 2009. It was planted on 20.6 million ha in 2015 (62% of the total crop). The technology offered the same tolerance to glyphosate as the first generation (and the same cost saving) but

with higher yielding potential. Pre-launch trials of the technology suggested that average yields would increase by between +7% and +11%. In assessing the impact on yield of this new generation of GM HT soybeans since 2009, it is important to recognise that only limited seed was initially available for planting in 2009 and the trait was not available in many of the leading (best performing) varieties. As a result, reports of first year performance²² were varied when compared with the first generation of GM HT soybeans (which was available in all leading varieties), with some farmers reporting no improvement in yield relative to first generation GM HT soybeans whilst others found significant improvements in yield, of up to +10%. In 2010, when the trait was available in many more of the leading varieties, farmer feedback to the seed/technology providers reports average yield improvements of about +5%. In subsequent years, the average yield gains reported were higher in the range of +9% to +11% (+8.9% 2015) relative to first generation GM HT and conventional soybean crops. Applying these yield gains plus the same cost saving assumptions as applied to first generation GM HT soybeans, but with a seed premium of \$65.21/ha for 2009, \$50.14/ha for 2010, \$62.5 for 2011, \$57.7/ha in 2012, \$62.05/ha in 2013, \$52.76/ha in 2014 and \$57.17/ha in 2015, the net impact on farm income in 2015, inclusive of yield gain, was +\$94.4/ha. Aggregated to the national level this was equal to an improvement in farm income of \$1.95 billion in 2015 and cumulatively since 2009, the total farm income gain has been \$10 billion. The technology also increased US soybean production by 22.7 million tonnes since 2009.

3.1.2 Argentina

As in the US, first generation GM HT soybeans were first planted commercially in 1996. Since then, use of the technology has increased rapidly and almost all soybeans grown in Argentina are GM HT (99%). The impact on farm income has been substantial, with farmers deriving important cost saving and farm income benefits both similar and additional to those obtained in the US (Table 11). More specifically:

- The impact on yield has been neutral (ie, no positive or negative yield impact);
- The cost of the technology to Argentine farmers has been substantially lower than in the US (about \$1/ha-\$4/ha compared to \$15/ha-\$50/ha in the US) mainly because the main technology provider (Monsanto) was not able to obtain patent protection for the technology in Argentina. As such, Argentine farmers have been free to save and use GM seed without paying any technology fees or royalties (on farm-saved seed) for many years;
- The savings from reduced expenditure on herbicides, fewer spray runs and machinery use have been in the range of \$24-\$30/ha, although since 2008, savings fell back to \$16/ha-\$26/ha because of the significant increase in the price of glyphosate relative to other herbicides in 2008-09 and additional expenditure on complementary herbicide use to address weed resistance (to glyphosate) issues. Net income gains have been in the range of \$21-\$29/ha up to 2007²³ and \$14/ha-\$24/ha since 2008;
- The price received by farmers for GM HT soybeans in the early years of adoption was, on average, marginally higher than for conventionally produced soybeans, because of lower

²² The authors are not aware of any survey-based assessment of performance in 2009

²³ This income gain also includes the benefits accruing from the fall in real price of glyphosate, which fell by about a third between 1996 and 2000

levels of weed material and impurities in the crop. This quality premia was equivalent to about 0.5% of the baseline price for soybeans (not applied in the analysis after 2006);

- The net income gain from use of the GM HT technology at a national level was \$448 million in 2015. Since 1996, the cumulative benefit (in nominal terms) has been \$6 billion;
- 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 farmers to cultivate two crops (wheat followed by soybeans) in one season. About 19% of the total Argentine soybean crop was second crop in 2015²⁴, compared to 8% in 1996. Based on the additional gross margin income derived from second crop soybeans (see Appendix 2), this has contributed a further boost to national soybean farm income of \$484 million in 2015 and \$11.35 billion cumulatively since 1996;
- The total farm income benefit inclusive of the second cropping was \$932 million in 2015 and \$17.37 billion cumulatively between 1996 and 2015.

Table 11: Farm level income impact of using GM HT soybeans in Argentina 1996-2015

Year	Cost savings (\$/ha)	Net saving on costs (inclusive of cost of technology: \$/ha)	Increase in farm income at a national level (\$ millions)	Increase in farm income from facilitating additional second cropping (\$ millions)
1996	26.10	22.49	0.9	0
1997	25.32	21.71	42	25
1998	24.71	21.10	115	43
1999	24.41	20.80	152	118
2000	24.31	20.70	205	143
2001	24.31	20.70	250	273
2002	29.00	27.82	372	373
2003	29.00	27.75	400	416
2004	30.00	28.77	436	678
2005	30.20	28.96	471	527
2006	28.72	26.22	465	699
2007	28.61	26.11	429	1,134
2008	16.37	13.87	230	754
2009	16.60	14.10	256	736
2010	18.30	15.80	285	1,134
2011	17.43	14.93	275	1,184
2012	16.48	13.98	269	845
2013	26.77	24.27	475	1,002
2014	25.41	22.91	436	784
2015	26.60	24.10	448	484

Sources and notes:

²⁴ The second crop share was about 3.7 million ha in 2015

1. The primary source of information for impact on the costs of production is Qaim & Traxler (2002 & 2005). This has been updated in recent years to reflect changes in herbicide prices and weed control practices
2. All values for prices and costs denominated in Argentine pesos have been converted to US dollars at the annual average exchange rate in each year
3. The second cropping benefits are based on the gross margin derived from second crop soybeans multiplied by the total area of second crop soybeans (less an assumed area of second crop soybeans that equals the second crop area in 1996 – this was discontinued from 2004 because of the importance farmers attach to the GM HT system in facilitating them remaining in no tillage production systems). The source of gross margin data comes from Grupo CEO and the Argentine Ministry of Agriculture
4. Additional information is available in Appendix 2
5. The net savings to costs understate the total gains in recent years because 70%-80% of GM HT plantings have been to farm-saved seed on which no seed premium was payable (relative to the \$3-\$4/ha premium charged for new seed)

3.1.3 Brazil

GM HT soybeans were probably first planted in Brazil in 1997. Since then, the area planted has increased to 94% of the total crop in 2015²⁵.

The impact of using GM HT soybeans has been similar to that identified in the US and Argentina. The net savings on herbicide costs have been larger in Brazil, due to higher average costs of weed control. Hence, the average cost savings arising from a combination of reduced herbicide use, fewer spray runs, labour and machinery savings, were between \$20/ha and \$81/ha in the period 2003 to 2015 (Table 12). The net cost saving after deduction of the technology fee (assumed to be about \$7/ha in 2015) has been between \$9/ha and \$60/ha in recent years. At a national level, the adoption of GM HT soybeans increased farm income levels by \$383 million in 2015. Cumulatively over the period 1997 to 2015, farm incomes have risen by \$6.7 billion (in nominal terms).

Table 12: Farm level income impact of using GM HT soybeans in Brazil 1997-2015

Year	Cost savings (\$/ha)	Net cost saving after inclusion of technology cost (\$/ha)	Impact on farm income at a national level (\$ millions)
1997	38.8	35.19	3.8
1998	42.12	38.51	20.5
1999	38.76	35.15	43.5
2000	65.32	31.71	43.7
2001	46.32	42.71	58.7
2002	40.00	36.39	66.7
2003	77.00	68.00	214.7
2004	76.66	61.66	320.9
2005	73.39	57.23	534.6
2006	81.09	61.32	730.6
2007	29.85	8.74	116.3
2008	64.07	44.44	591.9
2009	47.93	27.68	448.4
2010	57.28	37.8	694.1

²⁵ Until 2003 all plantings were technically illegal

2011	45.57	20.76	426.2
2012	32.27	20.75	511.1
2013	42.2	30.14	766.7
2014	41.28	30.23	724.9
2015	26.79	19.67	383.5

Sources and notes:

1. Impact data based on 2004 comparison data from the Parana Department of Agriculture (2004) Cost of production comparison: biotech and conventional soybeans, in USDA GAIN report BR4629 of 11 November 2004. www.fas.usad.gov/gainfiles/200411/146118108.pdf for the period to 2006. From 2007 based on Galvao (2009, 2010, 2012, 2013, 2014, 2015)
2. Cost of the technology from 2003 is based on the royalty payments officially levied by the technology providers. For years up to 2002, the cost of technology is based on costs of buying new seed in Argentina (the source of the seed). This probably overstates the real cost of the technology and understates the cost savings
3. All values for prices and costs denominated in Brazilian Real have been converted to US dollars at the annual average exchange rate in each year

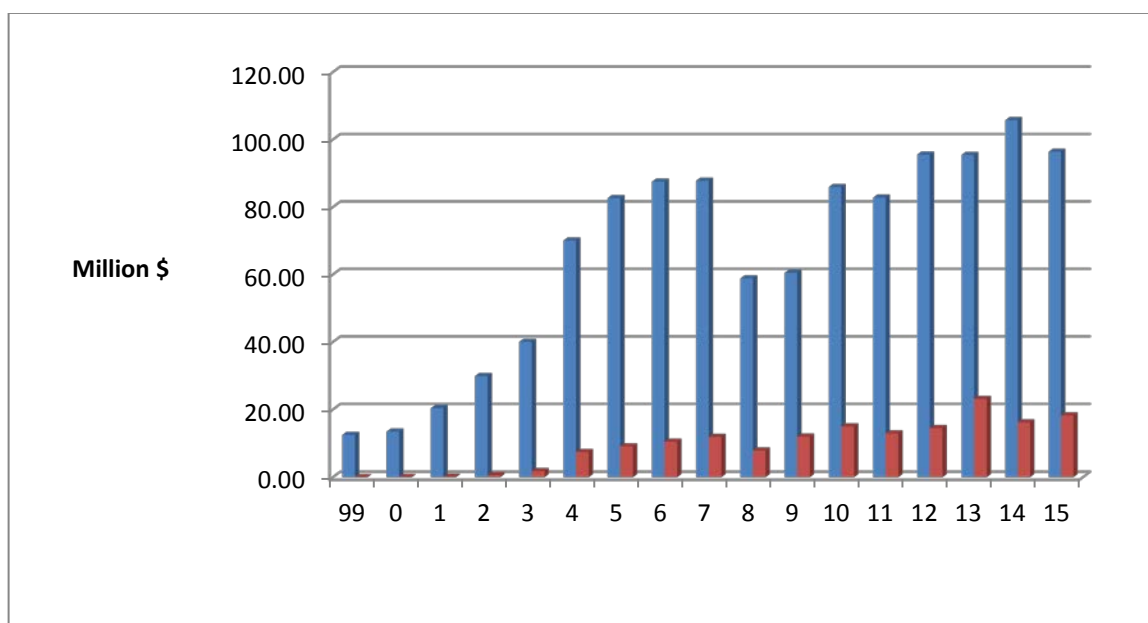
3.1.4 Paraguay and Uruguay

GM HT soybeans have been grown since 1999 and 2000 respectively in Paraguay and Uruguay. In 2015, they accounted for 94% of total soybean plantings in Paraguay and 100% of the soybean plantings in Uruguay²⁶. Using the original farm level impact data derived from Argentine research (on conventional alternatives) and applying this to production in these two countries together with subsequent updating of GM HT production that reflects changes in herbicide usage and cost data (source AMIS Global)²⁷, Figure 6 summarises the national farm level income benefits that have been derived from using the technology. In 2015, the respective national farm income gains were \$48.7 million in Paraguay (\$96.4 million including second crop benefits) and \$18.3 million in Uruguay.

²⁶ As in Argentina, the majority of plantings are to farm saved or uncertified seed

²⁷ Qaim & Traxler (2002 & 2005). The authors are not aware of any specific impact research having been conducted and published in Paraguay or Uruguay. Cost of herbicide data for recent years has been updated to reflect price and weed control practice changes in these countries (source: based on AMIS Global)

Figure 6: National farm income benefit from using GM HT soybeans in Paraguay and Uruguay 1999-2015 (million \$)



3.1.5 Canada

First generation GM HT soybeans

GM HT soybeans were first planted in Canada in 1997. In 2015, the share of total plantings accounted for by first generation GM HT soybeans was 26% (0.57 million ha).

At the farm level, the main impacts of use have been similar to the impacts in the US. The average farm income benefit has been within a range of \$14/ha-\$45/ha and the increase in farm income at the national level was \$22.5 million in 2015 (Table 13). The cumulative increase in farm income since 1997 has been \$188.6 million (in nominal terms).

Table 13: Farm level income impact of using GM HT soybeans (first generation) in Canada 1997-2015

Year	Cost savings (\$/ha)	Net cost saving/increase in gross margin (inclusive of technology cost: \$/ha)	Impact on farm income at a national level (\$ millions)
1997	64.28	41.17	0.041
1998	56.62	35.05	1.72
1999	53.17	31.64	6.35
2000	53.20	31.65	6.71
2001	49.83	29.17	9.35
2002	47.78	27.39	11.92
2003	49.46	14.64	7.65
2004	51.61	17.48	11.58
2005	55.65	18.85	13.30
2006	59.48	23.53	17.99
2007	61.99	24.52	16.87

2008	56.59	14.33	12.61
2009	55.01	14.54	12.66
2010	43.93	16.83	12.43
2011	44.31	17.72	9.45
2012	45.20	18.71	10.2
2013	45.05	19.50	2.55
2014	42.0	18.16	2.30
2015	74.84	39.66	22.5

Sources and notes:

1. Impact data based on George Morris Centre Report 2004 and updated in recent years to reflect changes in herbicide prices and weed control practices
2. All values for prices and costs denominated in Canadian dollars have been converted to US dollars at the annual average exchange rate in each year

Second generation GM HT soybeans

As in the US, 2009 was the first year of commercial availability of second generation GM HT soybeans. Seed containing this trait was planted on 1.3 million ha in 2015, equal to 59% of the total crop. In the absence of Canadian-specific impact data, we have applied the same cost of technology and yield impact assumptions as used in the analysis of impact in the US. On this basis, the net impact on farm income was +\$98.6/ha in 2015, with an aggregate increase in farm income of +\$127.7 million. Since 2009, the total farm income gain has been \$567 million.

3.1.6 South Africa

The first year GM HT soybeans were planted commercially in South Africa was 2001. In 2015 478,000 hectares (95%) of total soybean plantings were to varieties containing the GM HT trait. In terms of impact at the farm level, net cost savings of between \$1/ha and \$9/ha have been achieved through reduced expenditure on herbicides (Table 14). At the national level, the increase in farm income was \$4.2 million in 2015. Cumulatively the farm income gain since 2001 has been \$22.2 million²⁸.

Table 14: Farm level income impact of using GM HT soybeans in South Africa 2001-2015

Year	Cost savings (\$/ha)	Net cost saving/increase in gross margin after inclusion of technology cost (\$/ha)	Impact on farm income at a national level (\$ millions)
2001	26.72	7.02	0.042
2002	21.82	5.72	0.097
2003	30.40	7.90	0.24
2004	34.94	9.14	0.46
2005	36.17	9.12	1.42
2006	33.96	5.17	0.83
2007	32.95	5.01	0.72
2008	25.38	1.77	0.32
2009	26.33	0.54	0.14
2010	33.64	5.56	1.97
2011	26.62	1.95	0.78
2012	28.20	4.51	2.10
2013	10.26	8.70	4.0

²⁸ This possibly understates the beneficial impact because it does not take into consideration any savings from reduced labour for hand weeding

2014	9.32	7.94	4.9
2015	9.90	8.72	4.2

Sources and notes:

1. Impact data (source: Monsanto South Africa)
2. All values for prices and costs denominated in South African Rand have been converted to US dollars at the annual average exchange rate in each year

3.1.7 Romania

In 2015, farmers in Romania are not permitted to plant GM HT soybeans, having joined the EU at the start of 2007 (the EU regulatory authorities have not completed the process of evaluating past applications for the approval for planting GM HT soybeans and currently there is no ongoing application for approval for planting first generation GM HT soybeans in the EU). The impact data presented below therefore covers the period 1999-2006.

The growing of GM HT soybeans in Romania had resulted in substantially greater net farm income gains per hectare than any of the other countries using the technology:

- Yield gains of an average of 31%²⁹ have been recorded. This yield gain has arisen from the substantial improvements in weed control³⁰. In recent years, as fields have been cleaned of problem weeds, the average yield gains have decreased and were reported at +13% in 2006³¹;
- The cost of the technology to farmers in Romania tended to be higher than other countries, with seed being sold in conjunction with the herbicide. For example, in the 2002-2006 period, the average cost of seed and herbicide per hectare was \$120/ha to \$130/ha. This relatively high cost, however, did not deter adoption of the technology because of the major yield gains, improvements in the quality of soybeans produced (less weed material in the beans sold to crushers which resulted in price premia being obtained³²) and cost savings derived;
- The average net increase in gross margin in 2006 was \$59/ha (an average of \$105/ha over the eight years of commercial use: Table 15);
- At the national level, the increase in farm income amounted to \$7.6 million in 2006. Cumulatively in the period 1999-2006 the increase in farm income was \$44.6 million (in nominal terms);
- The yield gains in 2006 were equivalent to a 9% increase in national production³³ (the annual average increase in production over the eight years was equal to 10.1%).

²⁹ Source: Brookes (2005)

³⁰ Weed infestation levels, particularly of difficult to control weeds such as Johnson grass, have been very high in Romania. This is largely a legacy of the economic transition during the 1990s which resulted in very low levels of farm income, abandonment of land and very low levels of weed control. As a result, the weed bank developed substantially and has subsequently been very difficult to control, until the GM HT soybean system became available (glyphosate has been the key to controlling difficult weeds like Johnson grass)

³¹ Source: Farmer survey conducted in 2006 on behalf of Monsanto Romania

³² Industry sources report that price premia for cleaner crops were no longer payable by crushers from 2005 and hence this element has been discontinued in the subsequent analysis

³³ Derived by calculating the yield gains made on the GM HT area and comparing this increase in production relative to total soybean production

Table 15: Farm level income impact of using herbicide tolerant soybeans in Romania 1999-2006

Year	Cost saving (\$/ha)	Cost savings net of cost of technology (\$/ha)	Net increase in gross margin (\$/ha)	Impact on farm income at a national level (\$ millions)	Increase in national farm income as % of farm level value of national production
1999	162.08	2.08	105.18	1.63	4.0
2000	140.30	-19.7	89.14	3.21	8.2
2001	147.33	-0.67	107.17	1.93	10.3
2002	167.80	32.8	157.41	5.19	14.6
2003	206.70	76.7	219.01	8.76	12.7
2004	63.33	8.81	135.86	9.51	13.7
2005	64.54	9.10	76.16	6.69	12.2
2006	64.99	9.10	58.79	7.64	9.3

Sources and notes:

1. Impact data (sources: Brookes (2005) and Monsanto Romania (2008)). Average yield increase 31% applied to all years to 2003 and reduced to +25% 2004, +19% 2005 and +13% 2006. Average improvement in price premia from high quality 2% applied to years 1999-2004
2. All values for prices and costs denominated in Romanian Lei have been converted to US dollars at the annual average exchange rate in each year
3. Technology cost includes cost of herbicides
4. The technology was not permitted to be planted from 2007 – due to Romania joining the EU

3.1.8 Mexico

GM HT soybeans were first planted commercially in Mexico in 1997 (on a trial basis), and in 2015, a continued 'trial area' of 17,750 ha (out of total plantings of 249,000 ha) were varieties containing the GM HT trait.

At the farm level, the main impacts of use have been a combination of yield increase (+9.1% in 2004 and 2005, +3.64% in 2006, +3.2% 2007, +2.4% 2008, +13% in 2009, +4% 2010-2012, +9.9% 2013, -2% in 2014 and -0.75% in 2015) and (herbicide) cost savings. The average farm income impact has been within a range of -\$3/ha and +\$89/ha (inclusive of yield impact, cost savings and after payment of the technology fee/seed premium. In 2015, the income effect was marginally negative, reflecting a small yield loss relative to the average yield of leading varieties of conventional soybeans grown in the regions where GM HT soybeans were trialed.

Table 16: Farm level income impact of using GM HT soybeans in Mexico 2004-2015

Year	Cost savings after inclusion of seed premium (\$/ha)	Net cost saving/increase in gross margin (inclusive of technology cost & yield gain: \$/ha)	Impact on farm income at a national level (\$ millions)
2004	49.44	82.34	1.18
2005	51.20	89.41	0.94
2006	51.20	72.98	0.51
2007	51.05	66.84	0.33
2008	33.05	54.13	0.54
2009	-12.79	59.55	1.01
2010	-12.84	9.29	0.19

2011	-12.25	12.71	0.19
2012	-12.32	23.42	0.15
2013	14.33	87.86	1.0
2014	18.81	0.08	0.01
2015	0.56	-3.03	-0.05

Sources and notes:

1. Impact data based on Monsanto, 2005, 2007, 2008, 2009, 2010, 2013, 2014, 2015. Reportes final del programa Soya Solución Faena en Chiapas. Monsanto Comercial
2. All values for prices and costs denominated in Mexican pesos have been converted to US dollars at the annual average exchange rate in each year
3. Negative yields in 2014 and 2015 reflect a combination of drought in the main regions where GM HT soybeans are grown and the trait not being available in some leading varieties

3.1.9 Bolivia

GM HT soybeans were officially permitted for planting in 2009, although 'illegal' plantings have occurred for several years. For the purposes of analysis in this section, impacts have been calculated back to 2005, when an estimated 0.3 million ha of soybeans used GM HT technology. In 2015, 1 million ha (80% of total crop) used GM HT technology.

The main impacts of the technology³⁴ have been (Table 17):

- An increase in yield arising from improved yield control. The research work conducted by Fernandez et al (2009) estimated a 30% yield difference between GM HT and conventional soybeans; although some of the yield gain reflected the use of poor quality conventional seed by some farmers. In our analysis, we have used a more conservative yield gain of +15% (based on industry views);
- GM HT soybeans are assumed to trade at a price discount to conventional soybeans of 2.7%, reflecting the higher price set for conventional soybeans by the Bolivian government in 2014;
- The cost of the technology to farmers has been \$3.3/ha and the cost savings equal to \$9.3/ha, resulting in a change of +\$6/ha to the overall cost of production;
- Overall in 2015, the average farm income gain from using GM HT soybeans was about \$84/ha, resulting in a total farm income gain of \$86 million. Cumulatively since 2005, the total farm income gain is estimated at \$722 million.

Table 17: Farm level income impact of using GM HT soybeans in Bolivia 2005-2015

Year	Net cost saving/increase in gross margin (inclusive of technology cost & yield gain: \$/ha)	Impact on farm income at a national level (\$ millions)
2005	39.73	12.08
2006	36.60	15.55
2007	44.40	19.45
2008	79.97	36.27
2009	89.91	59.61
2010	103.13	80.15
2011	106.68	105.69

³⁴ Based on Fernandez et al (2009)

2012	109.60	105.22
2013	102.75	93.81
2014	101.01	107.31
2015	84.08	86.09

Sources and notes:

1. Impact data based on Fernandez et al (2009). Average yield gain assumed +15%, cost of technology \$3.32/ha

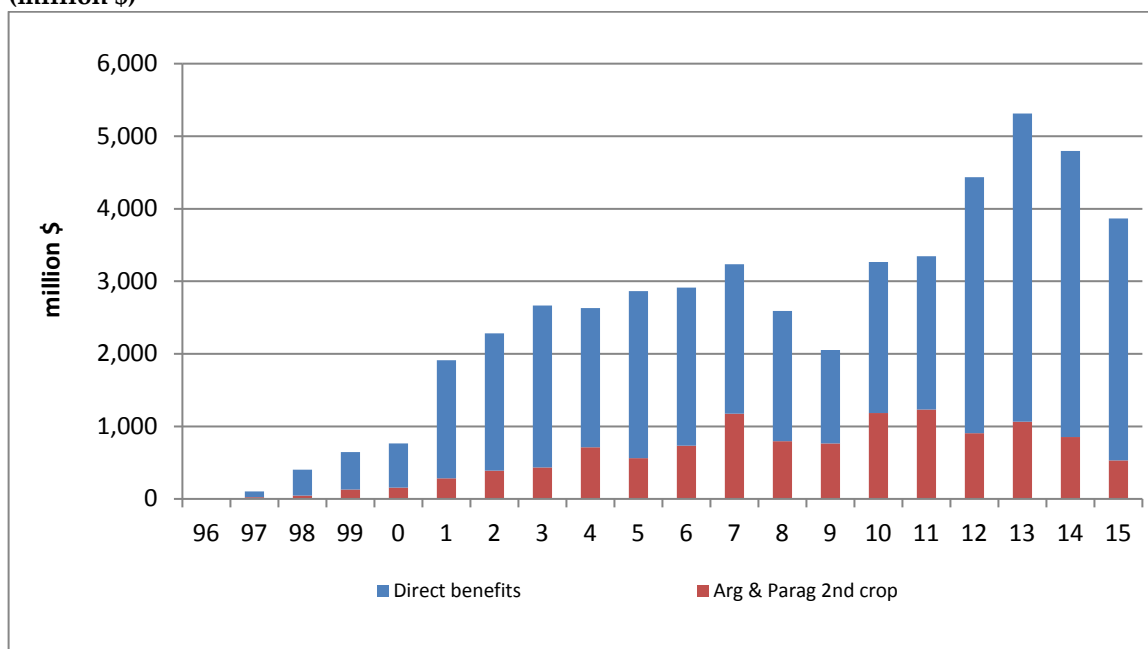
3.1.10 Summary of global economic impact

In global terms, the farm level impact of using GM HT technology in soybeans (excluding Intacta: see section 3.2) was \$3.29 billion in 2015 (Figure 9). If the second crop benefits arising in Argentina are included this rises to \$3.82 billion. Cumulatively since 1996, the farm income benefit has been (in nominal terms) \$38.1 billion (\$50.04 billion if second crop gains in Argentina and Paraguay are included).

In terms of the total value of global soybean production in 2015, the additional farm income (inclusive of Argentine second crop gains) generated by the technology is equal to a value added equivalent of 4.2%.

These economic benefits should be placed within the context of a significant increase in the level of soybean production in the main GM adopting countries since 1996 (more than a doubling in the area planted in the leading soybean producing countries of the US, Brazil and Argentina).

Figure 7: Global farm level income benefits derived from using GM HT soybeans 1996-2015 (million \$)



These economic benefits mostly derive from cost savings although farmers in Mexico, Bolivia and Romania also obtained yield gains (from significant improvements in weed control levels relative to levels applicable prior to the introduction of the technology). In addition, the availability of second generation GM HT soybeans in North America since 2009 is also delivering yield gains. If it is also assumed that all of the second crop soybean gains are effectively additional production

that would not otherwise have occurred without the GM HT technology (the GM HT technology facilitated major expansion of second crop soybeans in Argentina and to a lesser extent in Paraguay), then these gains are *de facto* 'yield' gains. Under this assumption, of the total cumulative farm income gains from using GM HT soybeans, \$23.6 billion (47%) is due to yield gains/second crop benefits and the balance, 53%, is due to cost savings.

3.2 Insect resistant soybeans

Second generation GM soybeans comprising both HT and IR traits (Intacta) were available to farmers in four South American countries for the first time in 2013-14. A summary of the adoption and key features of impact in 2015-16 is shown in Table 18. The total farm income gain recorded on a total usage area of 12.8 million ha was \$1.23 billion.

Table 18: Main impacts of insect resistant soybeans 2015/16

	Area planted (‘000 ha)	Average yield gain (%)	Average cost saving from reduced insecticide use (\$/ha)	Average farm income gain (\$/ha)	Aggregate farm income gain (million \$)
Brazil	11,800	+9.4	10.96	98.6	1,164.0
Argentina	700	+7.1	11.05	62.5	43.77
Paraguay	98	+9.1	40.0	91.6	8.97
Uruguay	200	+7.0	19.0	50.4	10.07
Total	12,798				1,226.81

Notes:

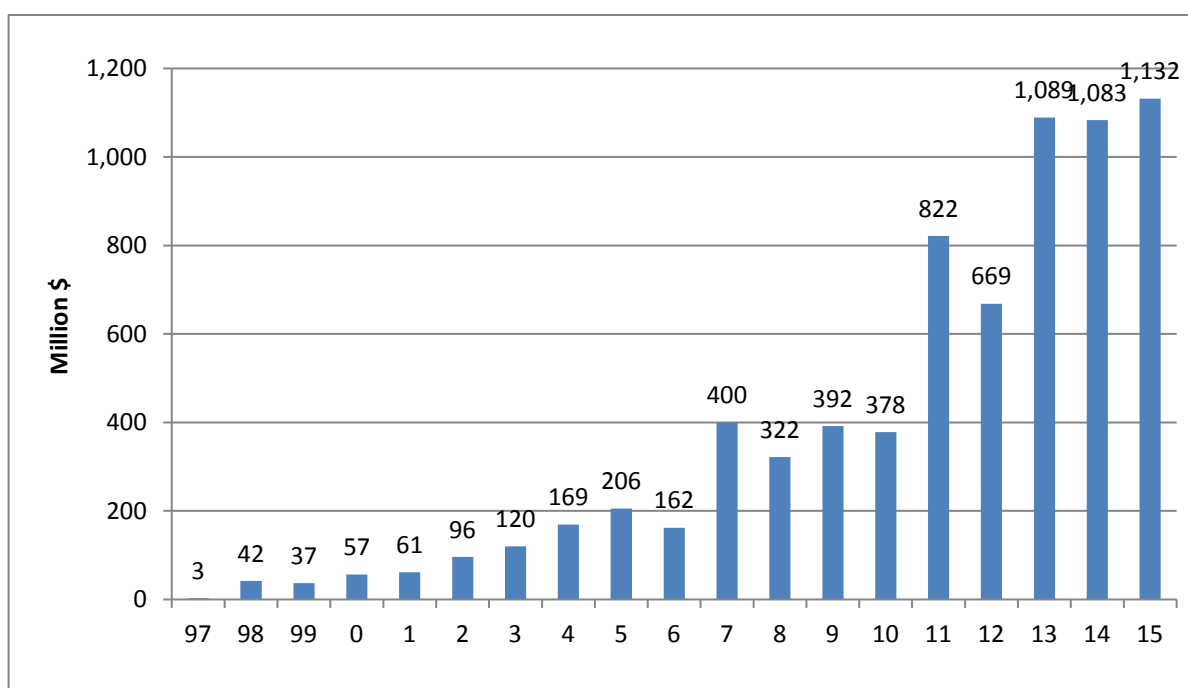
1. Impact data based on pre-commercial trials in 2011 and 2013 and post production farm survey (post market monitoring: Monsanto)
2. Cost of technology - \$30/ha all countries
3. Overall impact on cost of production also includes herbicide cost savings, as indicated in section 3.1 for first generation HT soybeans

3.3 Herbicide tolerant maize

3.3.1 The US

Herbicide tolerant maize³⁵ has been used commercially in the US since 1997 and in 2015 was planted on 89% of the total US maize crop. The impact of using this technology at the farm level is summarised in Figure 8. As with herbicide tolerant soybeans, the main benefit has been to reduce costs, and hence improve profitability levels. Average profitability improved by \$20/ha-\$36/ha in most years, although in 2008-09 this fell to a range of \$12/ha-\$16/ha, largely due to the significant increase in glyphosate prices relative to other herbicides. The net gain to farm income in 2015 was \$1,132 million and cumulatively, since 1997, the farm income benefit has been \$7.24 billion.

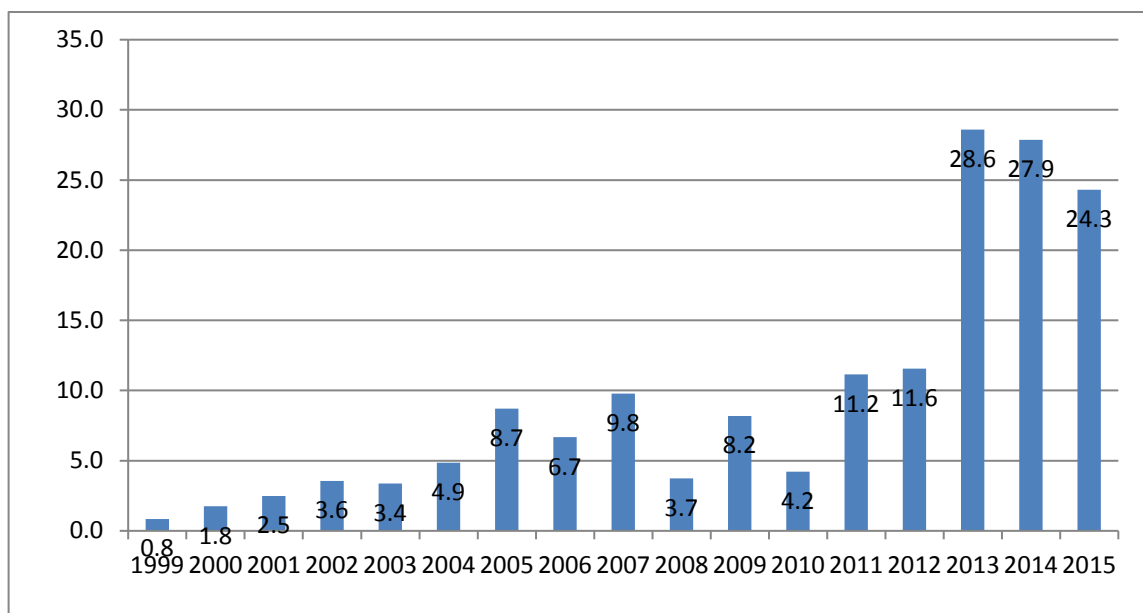
³⁵ Tolerant to glufosinate ammonium or to glyphosate, although cultivars tolerant to glyphosate have accounted for the majority of plantings

Figure 8: National farm income impact of using GM HT maize in the US 1997-2015 (million \$)

Source and notes: Impact analysis based on Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006), Johnson & Strom (2008) and updated from 2008 to reflect changes in herbicide prices and typical weed control programmes. Estimated cost of the technology \$14.83/ha in years up to 2004, \$17.3/ha in 2005, \$24.71/ha 2006-2007, \$17.94/ha 2008, \$21.29/ha in 2009, \$24.65/ha in 2010, \$24.41/ha in 2011, \$25/ha in 2012, \$30/ha 2013, \$28/ha 2014, \$29/ha 2015. Cost savings (mostly from lower herbicide use) \$38.47/ha in 2004, \$38.61/ha 2005, \$29.27/ha 2006, \$42.28/ha 2007, \$39.29/ha 2008, \$39.18 in 2009, \$41.12/ha 2010, \$57.64/ha 2011, \$50.88 2012, \$63.14/ha 2013, \$64.5/ha 2014, \$67.8/ha 2015

3.3.2 Canada

In Canada, GM HT maize was first planted commercially in 1999. In 2015, the proportion of total plantings accounted for by varieties containing a GM HT trait was 97%. As in the US, the main benefit has been to reduce costs and to improve profitability levels. Average annual profitability has improved by between \$12/ha and \$18/ha up to 2007, but fell in 2008-09 to under \$10/ha due mainly to the higher price increases for glyphosate relative to other herbicides. In 2015, the net increase in farm income was \$24.3 million and cumulatively since 1999 the farm income benefit has been \$161.6 million (Figure 9).

Figure 9: National farm income impact of using GM HT maize in Canada 1999-2015 (\$ million)

Source and notes: Impact analysis based on data supplied by Monsanto Canada. Estimated cost of the technology \$18-\$35/ha, cost savings (mostly from lower herbicide use) \$31-\$55/ha

3.3.3 Argentina

GM HT maize was first planted commercially in Argentina in 2004, and in 2015, varieties containing a GM HT trait were planted on 2.23 million ha (64% of the total maize area). It has been adopted in two distinct types of area, the majority (80%) in the traditional 'corn production belt' and 20% in newer maize-growing regions, which have traditionally been known as more marginal areas that surround the 'Corn Belt'. The limited adoption of GM HT technology in Argentina up to 2006 was mainly due to the technology only being available as a single gene, not stacked with the GM IR trait, which most maize growers have also adopted. Hence, faced with either a GM HT or a GM IR trait available for use, most farmers have chosen the GM IR trait because the additional returns derived from adoption have tended to be (on average) greater from the GM IR trait than the GM HT trait (see below for further details of returns from the GM HT trait). Stacked traits became available in 2007 and contributed to the significant increase in the GM HT maize area in subsequent years. In 2015, stacked-traited seed accounted for 89% of the total GM HT area.

In relation to impact on farm income, this can be examined from two perspectives; as a single GM HT trait and as a stacked trait. This differential nature of impact largely reflects the locations in which the different (single or stacked-traited seed) has tended to be used:

Single GM HT traited seed

- In all regions the cost of the technology (about \$20-\$30/ha) has been broadly equal to the saving in herbicide costs;
- In the 'Corn Belt' area, use of the single trait technology has resulted in an average 3% yield improvement via improved weed control. In the more marginal areas, the yield impact has been much more significant (+22%) as farmers have been able to significantly improve weed control levels;

- In 2015, the additional farm income at a national level, from using single traited GM HT technology, has been +\$25.6 million, and cumulatively since 2004, the income gain has been \$271.9 million.

Stacked-traited GM HT seed

- The average yield gain identified since adoption has been +15.75%³⁶. Given the average yield impact identified for the early years of adoption of the single traited GM IR maize was +5.5% (see section 3.7), our analysis has applied this level of impact to the GM IR component of the study (section 3.7), with the balance attributed to the GM HT trait. Hence, for the purposes of this analysis, the assumed yield effect of the GM HT trait on the area planted to GM stacked maize seed is +10.25%;
- The cost of the technology (seed premium) applied to GM HT component has been in a range of \$12/ha to \$41/ha, with the impact on costs of production (other than seed) assumed to be the same as for single-traited seed;
- Based on these assumptions, the net impact on farm income in 2015 was +\$144.8ha, giving an aggregated national level farm income gain of \$289 million. Cumulatively since 2007, the farm income gain has been \$1,424.2 million.

3.3.4 South Africa

Herbicide tolerant maize has been grown commercially in South Africa since 2003, and in 2015, 1.65 million hectares out of total plantings of 2.6 million hectares used this trait. Farmers using the technology have found small net savings in the cost of production (ie, the cost saving from reduced expenditure on herbicides has been greater than the cost of the technology), although in 2008 and 2009, due to the significant rise in the global price of glyphosate relative to other herbicides, the net farm income balance has been negative, at about -\$2/ha. In 2015, the net impact of use of the technology was +\$10.5/ha. At the national level, this is equivalent to a net gain of about \$17.3 million. Since 2003, there has been a net cumulative income gain of \$65.6 million. Readers should note that these cost savings do not take into consideration any labour cost saving that may arise from reduced need for hand weeding. For example, Regier G et al (2013) identified amongst small farmers in KwaZulu-Natal, savings of over \$80/ha from reduced requirement for hand weeding with the adoption of GM HT maize. Also it should be noted that Gouse et al (2012) found that small farmers (who account for about 5% of total maize production) obtained yield gains of between +3% and +8% when using this technology relative to conventional maize growing in which hand weeding was the primary form of weed control practice.

3.3.5 Philippines

GM HT maize was first grown commercially in 2006, and in 2015 was planted on 702,000 hectares. The impact of the technology in the first two years of adoption (based on industry sources) was of average yield gains of 15%. Based on a cost of the technology of \$24-\$27/ha (and assuming no net cost savings), the net national impacts on farm income in 2006 and 2007 were +\$0.98 million and +\$10.4 million respectively. More detailed analysis by Gonsales et al (2009) identified an average yield gain of +5%, the same cost of technology of \$24/ha-\$27/ha and a cost saving (reduced weed control costs from reduced cost of herbicides and less hand weeding) of \$35/ha-\$51/ha. These cost estimates have formed the basis of our analysis in subsequent years,

³⁶ Based on farm level feedback/surveys to the technology providers

although the mix of herbicides used, their prices and the cost of the technology have been adjusted based on industry and market research sources (AMIS Global). In 2015, our estimates are that the net farm income gain from using GM HT maize was +\$21.5/ha, which at the national level was equal to +\$15.1 million. Cumulatively, since 2006, the total farm income gain has been \$156.6 million.

3.3.6 Brazil

2015 was the sixth year in which GM HT maize was planted in Brazil (on 63% of the total crop: 7.98 million ha). Based on analysis by Galvao (2010-2015), the technology is estimated to have delivered a yield gain of 2.5% in 2010, 3.6% in 2011 and 6.8% in 2012 and 2013 and +3% in 2014 and 2015. The technology (seed premium) costs have been in the range of \$10/ha-\$32/ha. In net farm income terms, inclusive of yield gain, the average farm income gain has been between \$25/ha and \$87/ha. At the national level, the farm income gain was \$281 million in 2015, and \$1.78 billion for the six years.

3.3.7 Colombia

GM HT maize was first planted in Colombia in 2009 and in 2015, 73,000 ha (15% of the total crop) used this technology (in the form of stacked traited seed, with GM IR technology). Analysis of its impact is limited, with a recent study by Mendez et al (2011) being the only publicly available material. This analysis focused only on a small area in one region of the country (San Juan valley) and therefore is unlikely to be fully representative of (potential) impact across the country. Nevertheless, as this represents the only available data, we have included it for illustrative purposes. The analysis identified a positive yield impact of +22% for the stacked traited seed (HT tolerance to glufosinate and IR resistance to corn boring pests) and for the purposes of our analysis, all of this yield gain has been included/attributed to the GM IR component of the technology, as presented in section 3.7.8. In terms of impact of costs of production, the GM HT part is estimated to have had a net positive impact on profitability of about \$10.1/ha in 2015 (seed premium of \$14/ha, counterbalanced by weed control cost savings of \$24/ha). At the national level, the total income gain in 2015 was \$0.74 million (\$4.49 million since 2009).

3.3.8 Uruguay

Maize farmers in Uruguay gained access to GM HT maize technology in 2011 (via stacked traited seed) and 73,000 ha of the country's 83,000 ha crop used this technology in 2015. Whilst the authors are not aware of any studies examining the impact of GM HT maize in Uruguay, applying impact and cost assumptions based on the neighbouring Argentina, suggests small levels of farm income gains of about \$9.8/ha, equal to about \$0.71 million at the national level in 2015 (\$1.87 million for the five years).

3.3.9 Paraguay

GM HT technology was used for the first time in 2013 in Paraguay, and in 2015, 35% of the country's maize crop (252,000 ha) used seed containing this trait. Based on a seed premium of \$13.3/ha (source: industry) and an estimated herbicide cost saving of about \$19.5/ha (sources: industry and AMIS Global 2013 and 2015), the farm income gain was about \$6/ha. At the

national level, this was equal to about \$1.56 million in 2015 and a cumulative gain of \$2.5 million since 2013.

3.3.9 Summary of global economic impact

In global terms, the farm level economic impact of using GM HT technology in maize was \$1.79 billion in 2015 (63% of which was in the US). Cumulatively since 1997, the farm income benefit has been (in nominal terms) \$11.1 billion. Of this, 69% has been due to cost savings and 31% to yield gains (from improved weed control relative to the level of weed control achieved by farmers using conventional technology).

The additional farm income generated by the technology is equal to a value-added equivalent of 1.0% of global maize production.

3.4 Herbicide tolerant cotton

3.4.1 The US

GM HT cotton was first grown commercially in the US in 1997 and in 2015 was planted on 89% of total cotton plantings³⁷.

The farm income impact of using GM HT cotton is summarised in Table 19. The primary benefit has been to reduce costs, and hence improve profitability levels, with annual average profitability increasing by between \$21/ha and \$49/ha³⁸ in the years up to 2004. Since then net income gains fell to between \$3/ha and \$18/ha. In 2015, the net income gain was \$3/ha. The relatively smaller positive impact on direct farm income in recent years reflects a combination of reasons, including the higher cost of the technology, significant price increases for glyphosate relative to price increases for other herbicides in 2008-09 and changes in weed control practices (additional costs) for the management of weeds resistant to glyphosate (notably *Palmer Amaranth*), as farmers have increasingly adopted integrated weed management strategies based on the use of mix of herbicides that complement the use of glyphosate. Overall, the net direct farm income impact in 2015 is estimated to be \$24.7 million (this does not take into consideration any non-pecuniary benefits associated with adoption of the technology: see section 3.10). Cumulatively since 1997 there has been a net farm income benefit from using the technology of \$1.1 billion.

³⁷ Although there have been GM HT cultivars tolerant to glyphosate and glufosinate, glyphosate tolerant cultivars have dominated

³⁸ The only published source that has examined the impact of HT cotton in the US is work by Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006) and Johnson & Strom (2008). In the 2001 study the costs saved were based on historic patterns of herbicides used on conventional cotton in the mid/late 1990s. The latter studies estimated cost savings on the basis of the conventional herbicide treatment that would be required to deliver the same level of weed control as GM HT cotton. Revised analysis has, however, been conducted annually from 2008 to reflect changes in the costs of production (notably cost of the technology, in particular 'Roundup Ready Flex technology'), higher prices for glyphosate relative to other herbicides particularly in 2008 & 2009 and additional costs incurred to control weeds resistant to glyphosate

Table 19: Farm level income impact of using GM HT cotton in the US 1997-2015

Year	Cost savings (\$/ha)	Net cost saving/increase in gross margins, inclusive of cost of technology (\$/ha)	Increase in farm income at a national level (\$ millions)
1997	34.12	21.28	12.56
1998	34.12	21.28	30.21
1999	34.12	21.28	53.91
2000	34.12	21.28	61.46
2001	65.59	45.27	161.46
2002	65.59	45.27	153.18
2003	65.59	45.27	129.75
2004	83.35	48.80	154.72
2005	71.12	2.89	9.57
2006	73.66	3.31	13.29
2007	76.01	5.40	16.56
2008	77.60	6.14	12.79
2009	83.69	7.49	18.96
2010	94.81	13.57	46.72
2011	99.24	17.64	49.33
2012	91.08	16.95	50.14
2013	94.73	20.60	51.71
2014	88.22	14.09	47.51
2015	77.14	3.01	24.68

Source and notes:

1. Impact analysis based on Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006) and Johnson & Strom (2008) and own analysis from 2008
2. Estimated cost of the technology \$12.85/ha (1997-2000) and \$21.32/ha 2001-2003, \$34.55 2004, \$68.22/ha 2005, \$70.35/ha 2006, \$70.61/ha 2007, \$71.56/ha 2008, \$76.2/ha 2009, \$81.24/ha 2010, \$81.6/ha 2011, \$74.13 2012-2015

3.4.2 Other countries

Australia, Argentina, South Africa, Mexico, Colombia and Brazil are the other countries where GM HT cotton is grown commercially; from 2000 in Australia, 2001 in South Africa, 2002 in Argentina, 2005 in Mexico, 2006 in Colombia and 2009 in Brazil. In 2015, 100% (270,000 ha), 100% (410,000 ha), 100% (9,100 ha), 96% (123,000 ha), 80% (16,000 ha) and 56% (540,000 ha) respectively of the total Australian, Argentine, South African, Mexican, Colombian and Brazilian cotton crops were planted to GM HT cultivars.

We are not aware of any published research into the impact of GM HT cotton in South Africa, Argentina, Mexico or Colombia. In Australia, although research has been conducted into the impact of using GM HT cotton (eg, Doyle et al (2003)) this does not provide quantification of the impact³⁹. Drawing on industry source estimates⁴⁰, the main impacts have been:

- *Australia*: no yield gain and cost of the technology in the range of \$30/ha to \$45/ha up to 2007. The cost of the technology increased with the availability of 'Roundup Ready Flex'

³⁹ This largely survey based research observed a wide variation of impact with yield and income gains widely reported for many farmers

⁴⁰ Sources: Monsanto Australia, Argentina, South Africa & Mexico

and in 2015 was \$56.3/ha. The cost savings from the technology (after taking into consideration the cost of the technology) have delivered small net gains of \$5/ha to \$7/ha, although estimates relating to the net average benefits from Roundup Ready Flex since becoming widely adopted from 2008 are higher (eg, \$48/ha in 2012). Overall, in 2015, the total farm income from using the technology was about \$7.6 million and cumulatively, since 2000, the total gains have been \$99.1 million;

- *Argentina*: no yield gain and an original cost of technology in the range of \$30/ha to \$40/ha, although with the increasing availability of stacked traits in recent years, the 'cost' part of the HT technology has fallen to about \$10/ha. Net farm income gains (after deduction of the cost of the technology) have been \$4/ha to \$28/ha and in 2015 was \$9.8/ha. Overall, in 2015, the total farm income from using GM HT cotton technology was \$16.9 million, and cumulatively since 2002, the farm income gain has been \$161.9 million;
- *South Africa*: no yield gain and a cost of technology in the range of \$13/ha to \$35/ha. Net farm income gains from cost savings (after deduction of the cost of the technology) have been \$35/ha to \$60/ha. In 2015, the average net gain was \$26/ha and the total farm income benefit of the technology was \$0.23 million. Cumulatively since 2001, the total farm income gain from GM HT cotton has been \$4.39 million;
- *Mexico*: average yield gains of +3.6% from improved weed control have been reported⁴¹ in the first three years of use, no yield gain was recorded in 2008 and yield gains of +5.1% in 2009, +18.1% in 2010 (since when Roundup Ready Flex technology has mainly been used), +5.1% 2011, +13.1% 2012, +14.2% 2013, +13.3% 2014 and +19.6% 2015. The average cost of the technology has been in the range of \$49/ha to \$79/ha. The typical net farm income gains were about \$80/ha in the first two years of use, \$16/ha in 2008 (when there was no yield gain), \$90/ha in 2009, \$446/ha in 2010, \$140/ha 2011, \$290/ha 2012, \$333/ha 2013, \$330/ha in 2014 and \$372/ha in 2015. Overall, in 2015 the total farm income gain from using GM HT cotton was \$45.8 million and cumulatively since 2005, the total farm income gain has been \$230.7 million;
- *Colombia*: average yield gain estimated at 4%, with a cost of technology at \$111/ha in 2015 and herbicide cost savings of \$128/ha. In 2015, this equates to a net increase in profitability of \$84/ha, which aggregated to the national level is an increase in farm income of \$1.33 million. Cumulatively since 2006, the total farm income gain has been \$24.3 million;
- *Brazil*: drawing on annual analysis by Galvão (2010-2015), the average yield gain has been between 1.8% and 3.7%, although in 2012 a net yield loss of 1.8% was reported relative to the best performing conventional seed. The technology fees (seed premium) have been in a range of \$26/ha to \$52/ha and net cost savings (after deducting the technology fee) have been between \$23/ha and \$90/ha. In 2015, the average farm income impact was +\$37/ha, which aggregated to the national level is equal to a farm income gain of \$20.2 million. Cumulatively, since 2009, the technology has contributed a total of \$153.5 million additional income to Brazilian cotton farmers.

3.4.3 Summary of global economic impact

Across the seven countries using GM HT cotton in 2015, the total farm income impact derived from using GM HT cotton was +\$116.7 million. Cumulatively since 1997, there have been net

⁴¹ Annual reports of Monsanto Mexico to the Mexican government

farm income gains of \$1.77 billion. Of this, 73% has been due to cost savings and 27% to yield gains (from improved weed control relative to the level of weed control achieved using conventional technology).

3.5 Herbicide tolerant canola

3.5.1 Canada

Canada was the first country to commercially use GM HT canola in 1996. Since then the area planted to varieties containing GM HT traits has increased significantly, and in 2015 was 93% of the total crop (7.53 million ha of GM HT crop).

The farm level impact of using GM HT canola in Canada since 1996 is summarised in Table 20. The key features are as follows:

- The primary impact in the early years of adoption was increased yields of almost 11% (eg, in 2002 this yield increase was equivalent to an increase in total Canadian canola production of nearly 7%). In addition, a small additional price premia was achieved from crushers through supplying cleaner crops (lower levels of weed impurities). With the development of hybrid varieties using conventional technology, the yield advantage of GM HT canola relative to conventional alternatives⁴² has been eroded. As a result, our analysis has applied the yield advantage of +10.7%, associated with the GM HT technology in its early years of adoption (source: Canola Council study of 2001), to 2003. From 2004 the yield gain has been based on differences between average annual variety trial results for 'Clearfield' (conventional herbicide tolerant varieties) and biotech alternatives (see notes to table for details). The biotech alternatives have also been differentiated into glyphosate tolerant and glufosinate tolerant. The quality premia associated with cleaner crops (see above) has not been included in the analysis from 2004;
- Cost of production (excluding the cost of the technology) has fallen, mainly through reduced expenditure on herbicides and some savings in fuel and labour. These savings have annually been between about \$25/ha and \$43/ha. The cost of the technology to 2003 was, however, marginally higher than these savings resulting in a net increase in costs of \$3/ha to \$5/ha. On the basis of comparing GM HT canola with 'Clearfield' HT canola (from 2004), there has, however been a net cost saving of \$6/ha and \$32/ha;
- The overall impact on profitability (inclusive of yield improvements and higher quality) has been an increase of between \$21/ha and \$48/ha, up to 2003. On the basis of comparing GM HT canola with 'Clearfield' HT canola (from 2004), the net increase in profitability has been between \$23/ha and \$81/ha;
- The annual total national farm income benefit from using the technology has risen from \$6 million in 1996 to \$610.6 million in 2015. The cumulative farm income benefit over the 1996-2015 period (in nominal terms) was \$5.07 billion.

⁴² The main one of which is 'Clearfield' conventionally derived herbicide tolerant varieties. Also hybrid canola now accounts for the majority of plantings (including some GM hybrids) with the hybrid vigour delivered by conventional breeding techniques (even in the GM HT (to glyphosate) varieties)

Table 20: Farm level income impact of using GM HT canola in Canada 1996-2015

Year	Cost savings (\$/ha)	Cost savings inclusive of cost of technology (\$/ha)	Net cost saving/increase in gross margins (\$/ha)	Increase in farm income at a national level (\$ millions)
1996	28.59	-4.13	45.11	6.23
1997	28.08	-4.05	37.11	21.69
1998	26.21	-3.78	36.93	70.18
1999	26.32	-3.79	30.63	90.33
2000	26.32	-3.79	22.42	59.91
2001	25.15	-1.62	23.10	53.34
2002	24.84	-3.59	29.63	61.86
2003	28.04	-4.05	41.42	132.08
2004	21.42	+4.44	19.09	70.72
2005	23.11	+4.50	32.90	148.12
2006	34.02	+16.93	50.71	233.13
2007	35.44	+17.46	66.39	341.44
2008	40.59	+22.45	69.82	389.94
2009	33.29	+13.52	55.40	321.42
2010	40.94	+22.78	78.46	475.34
2011	51.65	+32.76	65.81	457.24
2012	47.52	+28.80	55.84	445.85
2013	23.79	+5.72	74.70	554.42
2014	20.67	+5.61	67.21	532.23
2015	21.48	+9.68	81.05	610.58

Sources and notes:

1. Impact data based on Canola Council study (2001) to 2003 and Gusta M et al (2009). Includes a 10.7% yield improvement and a 1.27% increase in the price premium earned (cleaner crop with lower levels of weed impurities) until 2003. After 2004 the yield gain has been based on differences between average annual variety trial results for 'Clearfield' and biotech alternatives. The biotech alternatives have also been differentiated into glyphosate tolerant and glufosinate tolerant. This resulted in; for GM glyphosate tolerant varieties no yield difference for 2004, 2005, 2008 and 2010, +4% 2006 and 2007, +1.67% 2009, +1.6% 2011, +1.5% 2012, +3.1% 2013, +3.4% 2014, +4.3% 2015. For GM glufosinate tolerant varieties, the yield differences were +12% 2004 and 2008, +19% 2005, +10% 2006 and 2007, +11.8% 2009, +10.9% 2010, +4.6% 2011, +4.8% 2012, +10.1% 2013, +11% 2014, +11.6% 2015
2. Negative values denote a net increase in the cost of production (ie, the cost of the technology was greater than the other cost (eg. on herbicides) reductions)
3. All values for prices and costs denominated in Canadian dollars have been converted to US dollars at the annual average exchange rate in each year

3.5.2 The US

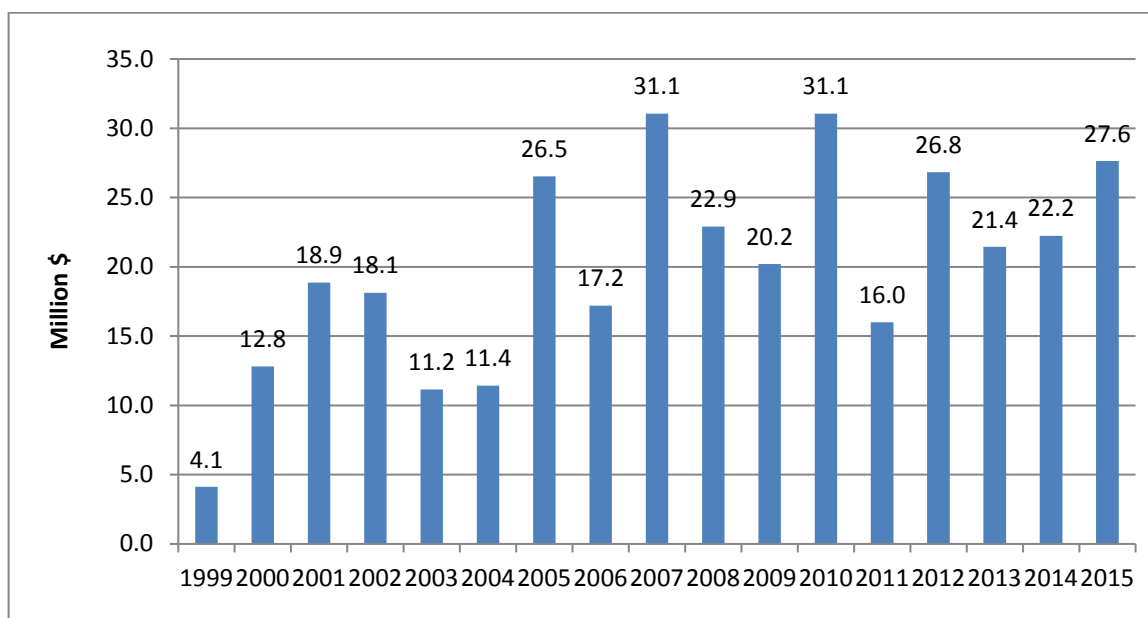
GM HT canola has been planted on a commercial basis in the US since 1999. In 2015, 93% of the US canola crop was GM HT (645,280 ha).

The farm level impact has been similar to the impact identified in Canada. More specifically:

- Average yields increased by about 6% in the initial years of adoption. As in Canada (see section 3.5.1) the availability of high yielding hybrid conventional varieties has eroded some of this yield gain relative to conventional alternatives. As a result, the positive

- yield impacts post 2004 have been applied on the same basis as in Canada (comparison with 'Clearfield': see section 3.5.1);
- The cost of the technology has been \$12/ha-\$17/ha for glufosinate tolerant varieties and \$12/ha-\$33/ha for glyphosate tolerant varieties. Cost savings (before inclusion of the technology costs) have been \$1/ha-\$45/ha (\$3/ha in 2015) for glufosinate tolerant canola and \$19-\$79/ha for glyphosate tolerant canola (\$19/ha 2015);
 - The net impact on gross margins has been between +\$22/ha and +\$90/ha (\$56.7/ha in 2015) for glufosinate tolerant canola, and between +\$23/ha and +\$61/ha for glyphosate tolerant canola (\$28.4/ha in 2015);
 - At the national level the total farm income benefit in 2015 was \$27.6 million (Figure 10) and the cumulative benefit since 1999 has been \$339.6 million.

Figure 10: National farm income impact: GM HT canola in the US 1999-2015 (million \$)



Source and notes: Impact analysis based on Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006), Johnson & Strom (2008) and updated from 2008 to reflect changes in herbicide prices and weed control practices. Decrease in total farm income impact 2002-2004 is due to decline in total plantings of canola in the US (from 612,000 in 2002 to 316,000 ha in 2004). Positive yield impact applied in the same way as Canada from 2004 – see section 3.5.1

3.5.3 Australia

GM HT canola was first planted for commercial use in 2008. In 2015, GM HT canola was planted on 444,000 ha. All of these plantings had tolerance to the herbicide glyphosate.

The main source of data on impact of this technology comes originally from a farm survey-based analysis of impact of the glyphosate tolerant canola, commissioned by Monsanto amongst 92 of the 108 farmers using this technology in 2008/09. Key findings from this survey were as follows:

- The technology was made available in both open pollinated and hybrid varieties, with the open pollinated varieties representing the cheaper end of the seed market, where

competition was mainly with open pollinated varieties containing herbicide tolerance (derived conventionally) to herbicides in the triazine (TT) group. The hybrid varieties containing glyphosate tolerance competed with non herbicide tolerant conventional hybrid varieties and herbicide tolerant 'Clearfield' hybrids (tolerant to the imidazolinone group of herbicides), although, where used in 2008, all of the 33 farmers in the survey using GM HT hybrids did so mainly in competition and comparison with 'Clearfield' varieties;

- The GM HT open pollinated varieties sold to farmers at a premium of about \$Aus3/ha (about \$2.5 US/ha) relative to the TT varieties. The GM HT hybrids sold at a seed premium of about \$Aus 9/ha (\$7.55 US/ha) compared to 'Clearfield' hybrids. In addition, farmers using the GM HT technology paid a 'technology' fee in two parts; one part was a set fee of \$Aus500 per farm plus a second part based on output - \$Aus 10.2/tonne of output of canola. On the basis that there were 108 farmers using GM HT (glyphosate tolerant) technology in 2008, the average 'up front' fee paid for the technology was \$Aus5.62/ha. On the basis of average yields obtained for the two main types of GM HT seed used, those using open pollinated varieties paid Aus \$11.83/ha (basis average yield of 1.16 tonnes/ha) and those using GM HT hybrids paid \$Aus12.95/ha (basis: average yield of 1.27 tonnes/ha). Therefore, the total seed premium and technology fee paid by farmers for the GM HT technology in 2008/09 was \$Aus20.45/ha (\$17.16 US/ha) for open pollinated varieties and \$Aus 27.57/ha (\$23.13 US/ha) for hybrid varieties. After taking into consideration the seed premium/technology fees, the GM HT system was marginally more expensive by \$Aus 3/ha (\$2.5 US/ha) and Aus \$4/ha (US \$3.36/ha) respectively for weed control than the TT and 'Clearfield' varieties;
- The GM HT varieties delivered higher average yields than their conventional counterparts: +22.11% compared to the TT varieties and +4.96% compared to the 'Clearfield' varieties. In addition, the GM HT varieties produced higher oil contents of +2% and +1.8% respectively compared to TT and 'Clearfield' varieties;
- The average reduction in weed control costs from using the GM HT system (excluding seed premium/technology fee) was \$Aus 17/ha for open pollinated varieties (competing with TT varieties) and \$Aus 24/ha for hybrids (competing with 'Clearfield' varieties).

In the analysis summarised in Table 21, we have applied these research findings to the total GM HT crop area on a weighted basis in which the results of GM HT open pollinated varieties that compete with TT varieties were applied to 64% of the total area in 2009 and 32% in 2010 and the balance of area used the results from the GM HT hybrids competing with 'Clearfield' varieties. This weighting reflects the distribution of farms in the survey. From 2011, yield differences identified in Hudson D and Richards R (2014) were used (a yield gain of about 14% relative to open pollinated triazine tolerant varieties and a yield reduction of about 0.2% relative to Clearfield hybrid canola again based on estimates of open pollination/hybrid seed sales). In addition, the seed premia has been adjusted to reflect changes that have occurred post 2008 (mostly reflecting the end part royalty part of the premia that is yield dependant). Cost differences between the different canola production systems were also updated from 2011 based on the findings of Hudson and Richards (2014) and changes in herbicide prices. The findings show an average farm income gain of US \$37.7/ha and a total farm income gain of \$16.7 million in 2015. Cumulatively since 2008, the total farm income gain has been \$73.9 million (Table 21).

It is noted that the share of GM HT canola has risen to only 20% of the total canola seed market and this suggests that the economic performance of GM HT canola relative to some of the

mainstream alternative production systems and seed types is not offering sufficient enough advantage to encourage wider take up of the technology. The recent analysis by Hudson and Richards (2014) provides insights into the impacts of the technology and shows that GM HT canola offers greatest economic advantage relative to TT canola and where farmers are faced with weeds that are resistant to a number of non-glyphosate herbicides (eg, annual ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*)). Relative to 'Clearfield' canola and conventional canola (that contains no HT traits, whether GM derived or not), GM HT canola is reported to offer little yield gain and the cost savings associated with reduced herbicide costs have tended to be more than offset by the cost of the technology. These factors may have been one of the main reasons for changes in the pricing of the GM HT technology introduced in 2012 which resulted in some reduction in the total seed premia level.

Table 21: Farm level income impact of using GM HT canola in Australia 2008-2015 (\$US)

Year	Average cost saving (\$/ha)	Average cost savings (net after cost of technology: \$/ha)	Average net increase in gross margins (\$/ha)	Increase in farm income at a national level ('000 \$)
2008	19.18	-20.76	96.87	978
2009	20.13	-21.08	95.14	3,919
2010	21.90	-10.13	57.27	7,635
2011	27.07	-5.97	29.74	4,138
2012	27.13	+5.41	44.77	8,105
2013	11.29	-1.26	67.94	15,108
2014	10.54	-1.18	45.59	17,332
2015	8.79	-0.98	37.73	16,738

Source derived from and based on Monsanto survey of licence holders 2008

Notes:

1. The average values shown are weighted averages
2. Other weighted average values derived include: yield +21.1% 2008, +20.9% 2009, +15.8% 2010, +7.6% 2011 and 2012, +11% 2013-2015. Quality (price) premium of 2.1% applied on the basis of this level of increase in average oil content. In 2010 because of a non GM canola price premia of 7%, the net impact on price was to apply a price discount of -4.9%. In 2011 because of a non GM canola price premia of 7%, the net impact on price was to apply a price discount of -2.9%. Since 2012, the price discount applied is -2%

3.5.4 Summary of global economic impact

In global terms, the farm level impact of using GM HT technology in canola in Canada, the US and Australia was \$655 million in 2015. Cumulatively since 1996, the farm income benefit has been (in nominal terms) \$5.48 billion. Within this, 75% has been due to yield gains and the balance (25%) has been from cost savings.

In terms of the total value of canola production in these three countries in 2015, the additional farm income generated by the technology is equal to a value-added equivalent of 8.1%. Relative to the value of global canola production in 2015, the farm income benefit added the equivalent of 2.4%.

3.6 GM herbicide tolerant (GM HT) sugar beet

3.6.1 US

GM HT sugar beet was first grown commercially in the US in 2007. In 2015, 454,270 hectares of GM HT sugar beet were planted, equal to 98% of the total US crop.

Impact of the technology in 2007 and 2008 has been identified as follows:

- a) *Yield*: analysis by Kniss (2008) covering a limited number of farms in Wyoming (2007) identified positive yield impacts of +8.8% in terms of additional root yield (from better weed control) and +12.6% in terms of sugar content relative to conventional crops (ie, the GM HT crop had about a 3.8% higher sugar content, which amounts to a 12.8% total sucrose gain relative to conventional sugar beet once the root yield gain was taken into consideration). In contrast, Khan (2008) found similar yields reported between conventional and GM HT sugar beet in the Red River Valley region (North Dakota) and Michigan. These contrasting results probably reflect a combination of factors including:
 - The sugar beet growing regions in Wyoming can probably be classified as high weed problem areas and, as such, are regions where obtaining effective weed control is difficult using conventional technology (timing of application is key to weed control in sugar beet, with optimal time for application being when weeds are small). Also, some weeds (eg, Kochia) are resistant to some of the commonly used ALS inhibitor herbicides like chlorsulfuron. The availability of GM HT sugar beet with its greater flexibility on application timing has therefore potentially delivered important yield gains for such growers;
 - The GM HT trait was not available in all leading varieties suitable in all growing regions in 2008, hence the yield benefits referred to above from better weed control have to some extent been counterbalanced by only being available in poorer performing germplasm in states like Michigan and North Dakota (notably not being available in 2008 in leading varieties with rhizomania resistance). It should be noted that the authors of the research cited in this section both perceive that yield benefits from using GM HT sugar beet will be a common feature of the technology in most regions once the technology is available in leading varieties;
 - 2008 was reported to have been, in the leading sugar beet growing states, a reasonable year for controlling weeds through conventional technology (ie, it was possible to get good levels of weed control through timely applications), hence the similar performance reported between the two systems.
- b) *Costs of production*
 - Kniss's work in Wyoming identified weed control costs (comprising herbicides, application, cultivation and hand labour) for conventional beet of \$437/ha compared to \$84/ha for the GM HT system. After taking into consideration the \$131/ha seed premium/technology fee for the GM HT trait, the net cost differences between the two systems was \$222/ha in favour of the GM HT system. Kniss did, however, acknowledge that the conventional costs associated with this sample were high relative to most producers (reflecting application of maximum dose rates for

herbicides and use of hand labour), with a more typical range of conventional weed control costs being between \$171/ha and \$319/ha (average \$245/ha);

- Khan's analysis puts the typical weed control costs in the Red River region of North Dakota to be about \$227/ha for conventional compared to \$91/ha for GM HT sugar beet. After taking into consideration the seed premium/technology fee (assumed by Khan to be \$158/ha⁴³), the total weed control costs were \$249/ha for the GM HT system, \$22/ha higher than the conventional system. Despite this net increase in average costs of production, most growers in this region used (and planned to continue using), the GM HT system because of the convenience and weed control flexibility benefits associated with it (which research by Marra and Piggot (2006): see section 3.10, estimated in the corn, soybean and cotton sectors to be valued at between \$12/ha and \$25/ha to US farmers). It is also likely that Khan's analysis may understate the total cost savings from using the technology by not taking into account savings on application costs and labour for hand weeding.

For the purposes of our analysis we have drawn on both these pieces of work and sought to update the impact assumptions based on experience post 2008. We are not aware of any published yield impact studies. Discussions with independent sugar beet analysts and industry representatives confirm that the early findings of research studies have been realised, with the technology delivering important yield improvements in some regions (those with difficult to control weeds, as identified by Kniss) but not so in other regions. The yield assumptions applied in the analysis below (Table 22) therefore continue to be based on the findings of the original two papers by Kniss and Khan. In relation to the seed premium and weed control costs, these have been updated to reflect changes in seed prices/premia, herbicide usage patterns and herbicide prices. This shows a net farm income gain in 2015 of \$52.1 million to US sugar beet farmers (average gain per hectare of \$114.7/ha). Cumulatively, the farm income gain, since 2007 has been \$400 million.

Table 22: Farm level income impact of using GM HT sugar beet in the US 2007-2015

Year	Average cost saving (\$/ha)	Average cost savings (net after cost of technology: \$/ha)	Average net increase in gross margins (\$/ha)	Increase in farm income at a national level ('000 \$)
2007	353.35	222.39	584.00	473
2008	141.50	-10.66	75.48	19,471.4
2009	142.5	-8.69	108.09	46,740.9
2010	142.5	-8.69	153.94	68,529.6
2011	101.81	-46.19	112.07	51,167.2
2012	101.81	-46.19	113.09	55,452.3
2013	149.81	+1.81	115.48	52,849.0
2014	154.22	+6.22	117.26	53,326.8
2015	157.69	+9.69	114.67	52,091.4

Sources derived from and based on Kniss (2008), Khan (2008), Jon Joseph Q et al (2010), Stachler J et al (2011) and GfK

Notes:

⁴³ Differences in the seed premium assumed by the different analysts reflect slightly different assumptions on seed rates used by farmers (the technology premium being charged per bag of seed)

1. The yield gains identified by Kniss have been applied to the 2007 GM HT plantings in total and to the estimated GM HT plantings in the states of Idaho, Wyoming, Nebraska and Colorado, where penetration of plantings in 2008 was 85% (these states account for 26% of the total GM HT crop in 2008), and which are perceived to be regions of above average weed problems. For all other regions, no yield gain is assumed. For 2008 onwards, this equates to a net average yield gain of +2.79%, +3.21%, +3.21%, +3.19%, +3.27%, +3.12%, +3.2%, +3.55% respectively for 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015
2. The seed premium of \$131/ha, average costs of weed control respectively for conventional and GM HT systems of \$245/ha and \$84/ha, from Kniss, were applied to the crop in Idaho, Wyoming, Nebraska and Colorado. The seed premium of \$158/ha, weed control costs of \$227/ha and \$249/ha respectively for conventional and GM HT sugar beet, identified by Khan, were applied to all other regions using the technology. The resulting average values for seed premium/cost of technology was \$152.16/ha 2008 and \$151.08/ha 2009 and 2010. Based on industry and extension service data for 2011, a seed premium of \$148/ha was used. The average weed control cost savings associated with the GM HT system (before taking into consideration the seed premium) were \$141.5/ha 2008 and \$142.5/ha 2009 and 2010, \$101.8/ha 2011 and 2012, \$149.81/ha 2013, \$154.22/ha 2014, \$157.69/ha 2015

3.6.2 Canada

GM HT sugar beet has also been used in the small Canadian sugar beet sector since 2008. In 2015, all of crop of 15,000 ha used this technology. We are not aware of any published analysis of the impact of GM HT sugar beet in Canada, but if the same assumptions used in the US are applied to Canada, the total farm income gain in 2015 was \$1.92 million and cumulatively since 2008, the income gain has been \$10.5 million.

3.7 GM insect resistant⁴⁴ (GM IR) maize

3.7.1 US

GM IR maize was first planted in the US in 1996 and in 2015 seed containing GM IR traits was planted on 81% (26.47 million ha) of the total US maize crop.

The farm level impact of using GM IR maize in the US since 1996 is summarised in Table 23:

- The primary impact has been increased average yields. Much of the analysis in early years of adoption (summarised for example in Marra et al (2002) and James (2002)) identified an average yield impact of about +5%. More comprehensive and recent work by Hutchison et al (2010) examined impacts over the 1996-2009 period and considered the positive yield impact on non GM IR crops of 'area-wide' adoption of the technology. The key finding of this work puts the average yield impact at +7%. This revised analysis has been used as the basis for our analysis below. In 2015, this additional production is equal to an increase in total US maize production of +6%;
- The net impact on cost of production has been a small increase of between \$1/ha and \$9/ha (additional cost of the technology being higher than the estimated average insecticide cost savings of \$15-\$16/ha). In the last few years however, with the rising cost of the technology⁴⁵, the net impact on costs has been an increase of \$7/ha to \$27/ha;

⁴⁴ The first generation being resistant to stalk boring pests but latter generations including resistance against cutworms and earworms

⁴⁵ Which tends to be mostly purchased as stacked-traited seed

- The annual total national farm income benefit from using the technology has risen from \$13.54 million in 1996 to \$2.17 billion in 2015. The cumulative farm income benefit over the 1996-2015 period (in nominal terms) was \$23.24 billion.

Table 23: Farm level income impact of using GM IR maize in the US 1996-2015

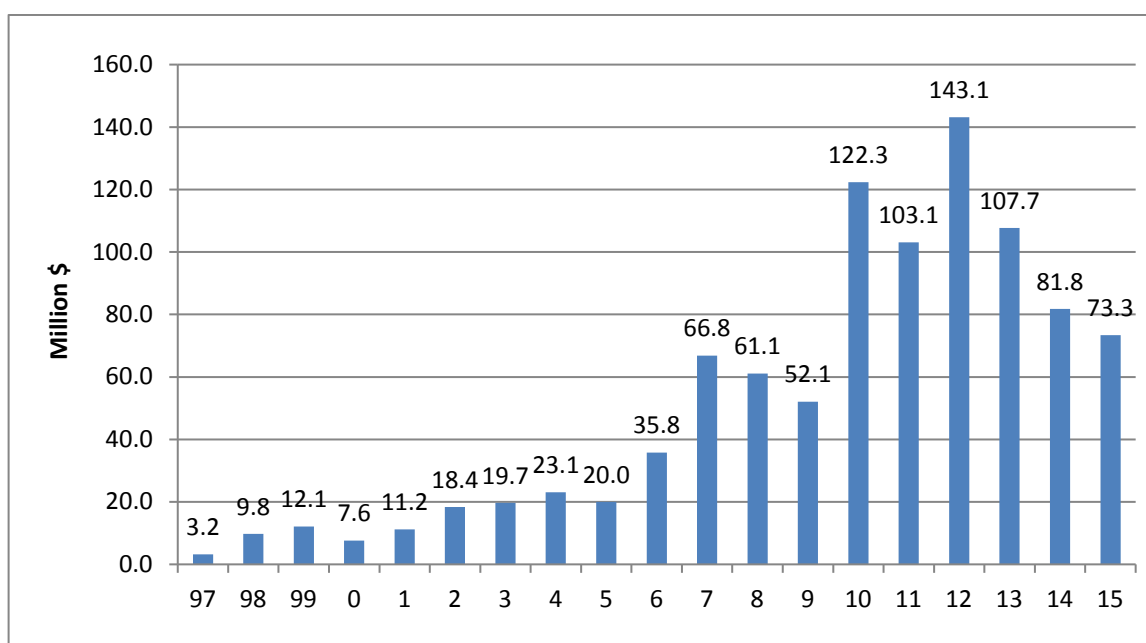
Year	Cost saving (\$/ha)	Cost savings (net after cost of technology: \$/ha)	Net increase in gross margins (\$/ha)	Increase in farm income at a national level (\$ millions)
1996	15.50	-9.21	45.53	13.54
1997	15.50	-9.21	39.38	96.0
1998	8.12	-12.18	27.93	179.2
1999	5.98	-14.32	23.63	188.5
2000	8.16	-14.08	25.37	163.3
2001	8.16	-14.08	28.34	160.0
2002	6.33	-15.91	30.96	234.7
2003	5.34	-16.90	31.22	297.9
2004	4.82	-17.42	33.84	420.0
2005	4.54	-12.76	33.15	381.4
2006	3.98	-13.33	55.23	752.4
2007	3.24	-14.06	66.05	1,375.9
2008	2.79	-14.13	89.20	1,755.7
2009	2.52	-18.14	78.81	1,738.2
2010	2.52	-21.40	87.43	1,799.7
2011	2.45	-21.25	127.20	3,101.9
2012	2.37	-21.87	114.15	2,905.1
2013	2.09	-24.14	98.13	2,875.9
2014	1.99	-25.50	89.58	2,628.9
2015	1.96	-26.04	74.86	2,170.8

Sources and notes:

1. Impact data based on a combination of studies including the ISAAA (James) review (2002), Marra et al (2002), Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006), Johnson & Strom (2008) and Hutchison et al (2010)
2. Yield impact +7% based on Hutchison et al (2010)
3. Insecticide cost savings based on the above references but applied to only 10% of the total crop area based on historic usage of insecticides targeted at stalk boring pests
4. – (minus) value for net cost savings means the cost of the technology is greater than the other cost savings

3.7.2 Canada

GM IR maize has also been grown commercially in Canada since 1996. In 2015, it accounted for 76% of the total Canadian maize crop of 1.3 million ha. The impact of GM IR maize in Canada has been very similar to the impact in the US (similar yield and cost of production impacts). At the national level, this equates to additional farm income generated from the use of GM IR maize of \$73.3 million in 2015 (Figure 11) and cumulatively since 1996, additional farm income (in nominal terms) of \$972 million.

Figure 11: National farm income impact: GM IR maize in Canada 1996-2015 (million \$)

Notes:

1. Yield increase of 7% based on US analysis. Cost of technology and insecticide cost savings also based on US analysis – insecticide cost savings constrained to 10% of total crop area to reflect historic insecticide use for stalk borer pest control
2. GM IR area planted in 1996 = 1,000 ha
3. All values for prices and costs denominated in Canadian dollars have been converted to US dollars at the annual average exchange rate in each year

3.7.3 Argentina

In 2015, GM IR maize traits were planted on 74% of the total Argentine maize crop (GM IR varieties were first planted in 1998).

The main impact of using the technology on farm profitability has been via yield increases. Various studies (eg, see ISAAA review in James (2002)) have identified an average yield increase in the region of 8% to 10%; hence an average of 9% has been used in the analysis up to 2004. More recent trade source estimates provided to the authors put the average yield increase in the last 4-5 years to be between 5% and 6%. Our analysis uses a yield increase value of 5.5% for the years from 2004 (see also note relating to yield impact of stacked-traited seed in section 3.3.3: GM HT maize in Argentina).

No savings in costs of production have arisen for most farmers because very few maize growers in Argentina have traditionally used insecticides as a method of control for corn boring pests. As such, average costs of production increased by \$20/ha-\$27/ha (the cost of the technology) in years up to 2006. From 2007, with stacked-traited seed becoming available and widely used, the additional cost of the technology relative to conventional seed has been in the range of \$10/ha-\$33/ha.

The net impact on farm profit margins (inclusive of the yield gain) has, in recent years, been an increase of \$3/ha to \$66/ha. In 2015, the national level impact on profitability was an increase of \$170.7 million. Cumulatively, the farm income gain, since 1998 has been \$946.7 million.

3.7.4 South Africa

GM IR maize has been grown commercially in South Africa since 2000. In 2015, 90% of the country's total maize crop of 2.6 million ha used GM IR cultivars.

The impact on farm profitability is summarised in Table 24. The main impact has been an average yield improvement of between 5% and 32% in the years 2000-2004, with an average of about 15% (used as the basis for analysis 2005-2007). In 2008 and 2009, the estimated yield impact was +10.6%⁴⁶ (this has been used as the basis of the analysis for 2010 onwards). The cost of the technology \$9/ha to \$17/ha has broadly been equal to the average cost savings from no longer applying insecticides to control corn borer pests.

At the national level, the increase in farm income in 2015 was \$213.6 million and cumulatively since 2000 it has been \$1.92 billion. In terms of national maize production, the use of GM IR technology has resulted in a net increase in national maize production of 9.5% in 2015.

Table 24: Farm level income impact of using GM IR maize in South Africa 2000-2015

Year	Cost savings (\$/ha)	Net cost savings inclusive of cost of technology (\$/ha)	Net increase in gross margin (\$/ha)	Impact on farm income at a national level (\$ millions)
2000	13.98	1.87	43.77	3.31
2001	11.27	1.51	34.60	4.46
2002	8.37	0.6	113.98	19.35
2003	12.82	0.4	63.72	14.66
2004	14.73	0.46	20.76	8.43
2005	15.25	0.47	48.66	19.03
2006	14.32	-2.36	63.75	63.05
2007	13.90	0.22	182.90	225.70
2008	11.74	-4.55	87.07	145.20
2009	12.83	-2.12	62.05	148.94
2010	13.97	-2.30	70.58	132.61
2011	12.27	-2.02	76.82	140.20
2012	11.81	-1.95	111.53	269.90
2013	10.05	-1.66	128.28	302.70
2014	8.94	-1.47	80.74	214.20
2015	7.60	-1.25	89.46	213.59

Sources and notes:

1. Impact data (sources: Gouse (2005 & 2006) and Van Der Weld (2009))
2. Negative value for the net cost saving = a net increase in costs (ie, the extra cost of the GM technology was greater than the savings from less expenditure on insecticides)
3. All values for prices and costs denominated in South African Rand have been converted to US dollars at the annual average exchange rate in each year

⁴⁶ Van der Weld (2009)

3.7.5 Spain

Spain has been commercially growing GM IR maize since 1998 and in 2015, 28% (107,750 ha) of the country's maize crop was planted to varieties containing a GM IR trait.

As in the other countries planting GM IR maize, the main impact on farm profitability has been increased yields (an average increase in yield of 6.3% across farms using the technology in the early years of adoption). With the availability and widespread adoption of the Mon 810 trait from 2003, the reported average positive yield impact is about +10%⁴⁷. There has also been a net annual average saving on cost of production (from lower insecticide use) of between \$37/ha and \$61/ha⁴⁸ in the early years of adoption (Table 25). This has been the basis of analysis to 2008. From 2009, the analysis draws on Riesgo et al (2012). At the national level, these yield gains and cost savings have resulted in farm income being boosted, in 2015, by \$19.6 million and cumulatively since 1998 the increase in farm income (in nominal terms) has been \$251.3 million.

Relative to national maize production, the yield increases derived from GM IR maize were equivalent to a 3.5% increase in national production (2015).

Table 25: Farm level income impact of using GM IR maize in Spain 1998-2015

Year	Cost savings (\$/ha)	Net cost savings inclusive of cost of technology (\$/ha)	Net increase in gross margin (\$/ha)	Impact on farm income at a national level (\$ millions)
1998	37.40	3.71	95.16	2.14
1999	44.81	12.80	102.20	2.56
2000	38.81	12.94	89.47	2.24
2001	37.63	21.05	95.63	1.10
2002	39.64	22.18	100.65	2.10
2003	47.50	26.58	121.68	3.93
2004	51.45	28.79	111.93	6.52
2005	52.33	8.72	144.74	7.70
2006	52.70	8.78	204.5	10.97
2007	57.30	9.55	274.59	20.63
2008	61.49	10.25	225.36	17.86
2009	8.82	-39.33	172.31	13.11
2010	8.80	-39.27	255.87	19.59
2011	8.46	-37.72	292.53	28.47
2012	8.24	-36.75	320.3	37.25
2013	8.51	-37.97	214.5	29.38
2014	8.50	-37.92	198.0	26.04
2015	7.11	-31.70	182.0	19.61

Sources and notes:

1. Impact data (based on Brookes (2003), Brookes (2008) and Riesgo et al (2012)). Yield impact +6.3% to 2004 and 10% 2005-2008, +12.6% 2009 onwards. Cost of technology based on €18.5/ha to 2004 and €35/ha from 2005, insecticide cost savings €42/ha to 2008, €6.4/ha 2009 onwards
2. All values for prices and costs denominated in Euros have been converted to US dollars at the annual average exchange rate in each year

⁴⁷ The cost of using this trait has been higher than the pre 2003 trait (Bt 176) – rising from about €20/ha to €35/ha

⁴⁸ Source: Brookes (2003) and Alcade (1999)

3.7.6 Other EU countries

A summary of the impact of GM IR technology in other countries of the EU is presented in Table 26. This shows that in 2015, the additional farm income derived from using GM IR technology in these four countries was about +\$1.36 million, and cumulatively over the period 2005-2015, the total income gain was \$23.6 million.

Table 26: Farm level income impact of using GM IR maize in other EU countries 2015

	Year first planted GM IR maize	Area (hectares)	Yield impact (%)	Cost of technology (\$/ha)	Cost savings (before deduction of cost of technology: \$/ha)	Net increase in gross margin (\$/ha)	Impact on farm income at a national level (million \$)
Portugal	2005	8,017	+12.5	38.8	0	158.77	1.27
Czech Republic	2005	997	+10	38.8	19.96	72.16	0.07
Slovakia	2005	104	+12.3	38.8	0	71.61	0.01
Romania	2007	3	+4.8%	35.48	0	38.2	0.01
Total other EU (excluding Spain)		9,121					1.36

Source and notes:

1. Source: based on Brookes (2008) and industry sources for yields in 2008 and 2009 in Romania
2. All values for prices and costs denominated in Euros have been converted to US dollars at the annual average exchange rate in each year

3.7.7 Brazil

Brazil first used GM IR maize technology in 2008. In 2015, 12.38 million ha of GM IR maize was planted (79% of the total crop). Analysis from Galvao (2009-2015) has been used as the basis for estimating the aggregate impacts on farm income and is presented in Table 27. In 2015, the total income gain was \$605.8 million, with the cumulative benefit since 2008 equal to \$5.39 billion.

Table 27: Farm level income impact of using GM IR maize in Brazil 2008-2015

Year	Cost savings (\$/ha)	Net cost savings inclusive of cost of technology (\$/ha)	Net increase in gross margin (\$/ha)	Impact on farm income at a national level (\$ millions)
2008	41.98	20.93	66.36	96.22
2009	44.21	-14.63	30.37	144.54
2010	48.60	-5.39	55.74	414.74
2011	23.13	-46.25	131.48	1,141.40
2012	13.35	-38.86	88.12	964.79
2013	18.22	-29.09	115.63	1,373.70
2014	16.69	50.93	54.72	651.70
2015	10.76	-32.85	48.92	605.78

Sources and notes:

1. Impact data (source : Galvão (2009-2015))

2. Negative value for the net cost savings = a net increase in costs (ie, the extra cost of the technology exceeded the savings on other costs (eg, less expenditure on insecticides)
3. All values for prices and costs denominated in Brazilian Real have been converted to US dollars at the annual average exchange rate in each year

3.7.8 Other countries

GM IR maize has been grown commercially in:

- *The Philippines* since 2003. In 2015, 645,840 hectares out of total plantings of 2.56 million (25%) were GM IR. Estimates of the impact of using GM IR (sources: Gonsales (2005), Yorobe (2004) and Ramon (2005)) show annual average yield increases in the range of 14.3% to 34%. The mid-point of this range (+24.15%) was used for the years 2003-2007. For 2008 onwards a yield impact of +18% has been used based on Gonsales et al (2009). Based on the findings of these research papers, a small average annual insecticide cost saving of about \$12/ha-\$15/ha and average cost of the technology of \$30/ha-\$47/ha have been used. The net impact on farm profitability has been between \$37/ha and \$118/ha. In 2015, the national farm income benefit derived from using the technology was \$66.8 million and cumulative farm income gain since 2003 has been \$485.1 million;
- *Uruguay* since 2004, and in 2015, 71,380 ha (86% of the total crop) were GM IR. Using Argentine data as the basis for assessing impact, the cumulative farm income gain has been \$28.1 million;
- *Honduras*. Here farm level 'trials' have been permitted since 2003, and in 2015, an estimated 27,000 ha used GM IR traits. Evidence from Falck Zepeda et al (2009) indicated that the primary impact of the technology has been to increase average yields (in 2008 +24%). As insecticides have not traditionally been used by most farmers, no costs of production savings have arisen. For the seed premium, no premia was charged during the trials period for growing (2003-2006), though for the purposes of our analysis, a seed premium of \$30/ha was assumed. From 2006, the seed premium applied is based on Falck-Zepeda et al (2009) at \$100/ha. Based on these costs, the estimated farm income benefit derived from the technology in 2015 was \$0.44 million and cumulatively since 2003 the income gain has been \$10.25 million;
- *Colombia*. GM IR maize has been grown on a 'trial basis' since 2007 in Colombia. In 2015, seed containing this technology was used on 14% of the crop (68,620 ha). Based on analysis from Mendez et al (2011) which explored impacts in one small region (San Juan valley), the average yield gain was +22%, the seed premium about \$47/ha and the savings in insecticide use equal to about \$53/ha (ie, a net cost saving of about \$6/ha). Inclusive of the yield gain, the average farm income gain in 2015 was \$305/ha. If aggregated to the whole of the GM IR area in 2015, this equates to a net farm income gain of \$20.9 million. Cumulatively since 2007, the net farm income gain has been about \$103.4 million;
- *Paraguay*. The first commercial crop of maize using this technology was grown in 2013-14. In 2015, 41% of the total crop (720,000 ha total crop) used seed containing this technology. Applying impact analysis from Argentina (in terms of average yield impacts and insecticide saving assumptions), together with a seed premium of about \$16/ha (source: Monsanto Paraguay), the average farm income gain from using the technology in 2015 was +\$32.9/ha. At the national level, this is equivalent to a total farm

income gain of \$9.77 million in 2015 and over the three years, the total farm income benefit has been \$22.87 million.

3.7.9 Summary of economic impact

In global terms, the farm level impact of using GM IR maize was \$3.36 billion in 2015.

Cumulatively since 1996, the benefit has been (in nominal terms) \$33.4 billion. This farm income gain has mostly derived from improved yields (less pest damage) although in some countries farmers have derived a net cost saving associated with reduced expenditure on insecticides.

In terms of the total value of maize production from the countries growing GM IR maize in 2015, the additional farm income generated by the technology is equal to a value-added equivalent of 4.5%. Relative to the value of global maize production in 2015, the farm income benefit added the equivalent of 2.4%.

3.8 Insect resistant (Bt) cotton (GM IR)

3.8.1 The US

GM IR cotton has been grown commercially in the US since 1996, and in 2015 was used on 84% (2.69 million ha) of total cotton plantings.

The farm income impact of using GM IR cotton is summarised in Table 28. The primary benefit has been increased yields (by 9%-11%), although small net savings in costs of production have also been obtained (reduced expenditure on insecticides being marginally greater than the cost of the technology for Bollgard I). Overall, average profitability levels increased by \$53/ha-\$115/ha with Bollgard I cotton (with a single Bt gene) between 1996 and 2002 and by between \$87/ha and \$151/ha in 2003-2015 with Bollgard II (containing two Bt genes and offering a broader spectrum of control). This resulted in a net gain to farm income in 2015 of \$271.8 million. Cumulatively, since 1996 the farm income benefit has been \$5.02 billion.

Table 28: Farm level income impact of using GM IR cotton in the US 1996-2015

Year	Cost savings (net after cost of technology: \$/ha)	Net increase in gross margins (\$/ha)	Increase in farm income at a national level (\$ millions)
1996	4.98	115.32	94.69
1997	4.98	103.47	87.28
1998	4.98	88.54	80.62
1999	4.98	65.47	127.29
2000	4.98	74.11	162.88
2001	4.98	53.04	125.22
2002	4.98	69.47	141.86
2003	5.78	120.49	239.98
2004	5.78	107.47	261.23
2005	24.48	117.81	332.41
2006	-5.77	86.61	305.17
2007	2.71	114.50	296.00
2008	2.71	98.22	189.50
2009	2.71	128.04	296.79
2010	-21.02	122.65	395.28

2011	-21.02	151.13	434.11
2012	-21.02	144.45	421.84
2013	-17.61	131.02	300.81
2014	-17.61	129.33	402.60
2015	-17.61	100.95	271.85

Sources and notes:

1. Impact data based on Gianessi & Carpenter (1999), Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006), Johnson & Strom (2008), Marra et al (2002) and Mullins & Hudson (2004)
2. Yield impact +9% 1996-2002 Bollgard I and +11% 2003-2004, +10% 2005 onwards Bollgard II
3. Cost of technology: 1996-2002 Bollgard I \$58.27/ha, 2003-2004 Bollgard II \$68.32/ha, \$49.62/ha 2005, \$46.95/ha 2006, \$25.7/ha 2007-2009, \$49.42 2010 onwards
4. Insecticide cost savings \$63.26/ha 1996-2002, \$74.10/ha 2003-2005, \$41.18/ha 2006, \$28.4/ha 2007-2012, \$31.81/ha 2013-2015

3.8.2 China

China first planted GM IR cotton in 1997, since when the area planted to GM IR varieties has increased to 96% of the total 3.1 million ha crop in 2015.

As in the US, a major farm income impact has been via higher yields of +8% to +10% on the crops using the technology, although there have also been significant cost savings on insecticides used and the labour previously used to undertake spraying. Overall, annual average costs have fallen (eg, by \$80/ha-\$90/ha in the last four years) and coupled with the yield gains, net returns have increased significantly. In 2015, the average increase in profitability was +\$338/ha, which equates to a net national gain of \$1 billion (Table 29). Cumulatively since 1997 the farm income benefit has been \$18.65 billion.

Table 29: Farm level income impact of using GM IR cotton in China 1997-2015

Year	Cost savings (net after cost of technology: \$/ha)	Net increase in gross margins (\$/ha)	Increase in farm income at a national level (\$ millions)
1997	194	333	11.33
1998	194	310	80.97
1999	200	278	181.67
2000	-14	123	150.18
2001	378	472	1,026.26
2002	194	327	687.27
2003	194	328	917.00
2004	194	299	1,105.26
2005	145	256	845.58
2006	146	226	792.28
2007	152	248	942.7
2008	167	244	933.7
2009	170	408	1,457.8
2010	176	503	1,736.5
2011	184	559	2,198.8
2012	27.5	401	1,583.7
2013	29.1	376	1,579.3
2014	28.2	319	1,306.8
2015	28.3	338	1,005.0

Sources and notes:

1. Impact data based on Pray et al (2002) which covered the years 1999-2001. Other years based on average of the 3 years, except 2005 onwards based on Shachuan (2006) – personal communication
2. Negative cost savings in 2000 reflect a year of high pest pressure (of pests not the target of GM IR technology) which resulted in above average use of insecticides on GM IR using farms
3. Yield impact +8% 1997-1999 and +10% 2000 onwards
4. Negative value for the net cost savings in 2000 = a net increase in costs (ie, the extra cost of the technology was greater than the savings on insecticide expenditure – a year of lower than average bollworm pest problems)
5. All values for prices and costs denominated in Chinese Yuan have been converted to US dollars at the annual average exchange rate in each year

3.8.3 Australia

Australia planted 94% of its 2015 cotton crop (total crop of 270,110 ha) to varieties containing GM IR traits (Australia first planted commercial GM IR cotton in 1996).

Unlike the other main countries using GM IR cotton, Australian growers have rarely derived yield gains from using the technology (reflecting the effective use of insecticides for pest control prior to the availability of GM IR cultivars); with the primary farm income benefit being derived from lower costs of production (Table 30). More specifically:

- In the first two years of adoption of the technology (Ingard, single gene Bt cotton), small net income losses were derived, mainly because of the relatively high price charged for the seed. Since this price was lowered in 1998, the net income impact has been positive, with cost savings of between \$54/ha and \$90/ha, mostly derived from lower insecticide costs (including application) more than offsetting the cost of the technology;
- For the last few years of use, Bollgard II cotton (containing two Bt genes) has been available offering effective control of a broader range of cotton pests. Despite the higher costs of this technology, users have continued to make significant net cost savings of \$186/ha to \$270/ha;
- At the national level in 2015, the net farm income gain was \$48.2 million and cumulatively since 1996 the gains have been \$849.94 million.

Table 30: Farm level income impact of using GM IR cotton in Australia 1996-2015

Year	Cost of technology (\$/ha)	Net increase in gross margins/cost saving after cost of technology (\$/ha)	Increase in farm income at a national level (\$ millions)
1996	-191.7	-41.0	-1.63
1997	-191.7	-35.0	-2.04
1998	-97.4	91.0	9.06
1999	-83.9	88.1	11.80
2000	-89.9	64.9	10.71
2001	-80.9	57.9	7.87
2002	-90.7	54.3	3.91
2003	-119.3	256.1	16.3
2004	-179.5	185.8	45.7
2005	-229.2	193.4	47.9
2006	-225.9	190.7	22.49
2007	-251.33	212.1	11.73
2008	-264.26	199.86	24.23
2009	-257.75	232.27	37.05
2010	-292.17	263.28	125.02

2011	-298.77	269.23	148.48
2012	-300.93	265.50	108.79
2013	-289.58	244.43	97.42
2014	-270.51	228.34	44.72
2015	-225.39	190.26	48.19

Sources and notes:

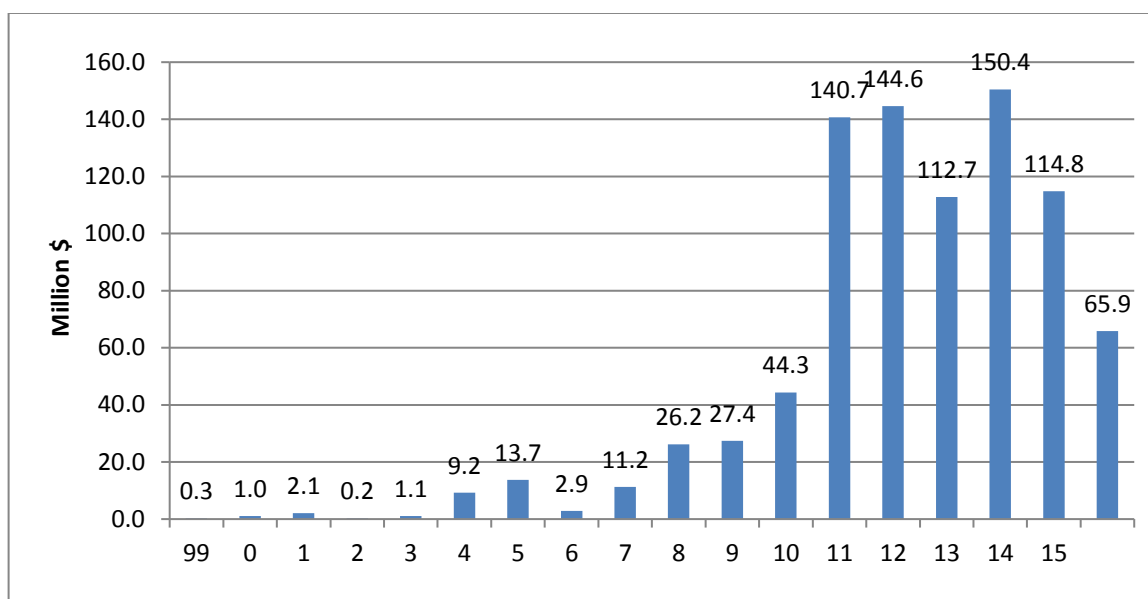
1. Impact data based on Fitt (2001) and CSIRO for bollgard II since 2004
2. All values for prices and costs denominated in Australian dollars have been converted to US dollars at the annual average exchange rate in each year

3.8.4 Argentina

GM IR cotton has been planted in Argentina since 1998. In 2015, it accounted for 92% of total cotton plantings.

The main impact in Argentina has been yield gains of 30%. This has more than offset the cost of using the technology⁴⁹. In terms of gross margin, cotton farmers have gained between \$25/ha and \$317/ha annually during the period 1998-2015⁵⁰. At the national level, the farm income gain was \$65.9 million (Figure 12). Cumulatively since 1998, the farm income gain from use of the technology has been \$868.8 million.

Figure 12: National farm income impact: GM IR cotton in Argentina 1998-2015 (million \$)



Sources and notes:

1. Impact data (source: Qaim & De Janvry (2002) and for 2005 and 2006 Monsanto LAP, although cost of technology in 2005 from Monsanto Argentina). Area data : source ArgenBio
2. Yield impact +30%, cost of technology \$86/ha (\$40/ha 2005), cost savings (reduced insecticide use) in the last five years \$54/ha-\$69/ha
3. All values for prices and costs denominated in Argentine Pesos have been converted to US dollars at the annual average exchange rate in each year

⁴⁹ The cost of the technology used in the years up to 2004 was \$86/ha (source: Qaim & DeJanvry). From 2005, the technology cost assumption has been 116 pesos/ha (\$20/ha- \$40/ha: source: Monsanto Argentina). The insecticide cost savings have been \$54/ha-\$74/ha

⁵⁰ The variation in margins has largely been due to the widely fluctuating annual price of cotton

3.8.5 Mexico

GM IR cotton has been planted commercially in Mexico since 1996. In 2015, GM IR cotton was planted on 118,080 ha (92% of total cotton plantings).

The main farm income impact of using the technology has been yield improvements of between 7% and 16% over the last ten years. In addition, there have been important savings in the cost of production (lower insecticide costs)⁵¹. Overall, the annual net increase in farm profitability has been within the range of \$104/ha and \$378/ha (Table 31). At the national level, the farm income benefit in 2015 was \$31.5 million and the impact on total cotton production was an increase of 14%. Cumulatively since 1996, the farm income benefit has been \$252.3 million.

Table 31: Farm level income impact of using GM IR cotton in Mexico 1996-2015

Year	Cost savings (net after cost of technology: \$/ha)	Net increase in gross margins (\$/ha)	Increase in farm income at a national level (\$ millions)
1996	58.1	354.5	0.3
1997	56.1	103.4	1.7
1998	38.4	316.4	11.3
1999	46.5	316.8	5.3
2000	47.0	262.4	6.8
2001	47.6	120.6	3.0
2002	46.1	120.8	1.8
2003	41.0	127.7	3.3
2004	39.3	130.4	6.2
2005	40.8	132.3	10.4
2006	20.4	124.4	6.4
2007	20.5	139.7	8.4
2008	19.9	150.4	10.5
2009	-22.16	253.2	7.7
2010	-40.81	220.8	10.9
2011	-37.61	290.3	29.0
2012	-60.16	127.0	12.7
2013	-57.75	199.5	19.9
2014	-40.71	378.3	58.26
2015	-49.33	266.92	31.52

Sources and notes:

1. Impact data based on Traxler et al (2001) covering the years 1997 and 1998. Yield changes in other years based on official reports submitted to the Mexican Ministry of Agriculture by Monsanto Comercial (Mexico)
2. Yield impacts: 1996 +37%, 1997 +3%, 1998 +20%, 1999 +27%, 2000 +17%, 2001 +9%, 2002 +7%, 2003 +6%, 2004 +7.6%, 2005 +9.25%, 2006 +9%, 2007 & 2008 +9.28%, 2009 +14.2%, 2010 and 2011 +10.3%, 2012 +7.17%, +8.95% 2013, +15.8% 2014, +15.3% 2015
3. All values for prices and costs denominated in Mexican Pesos have been converted to US dollars at the annual average exchange rate in each year

⁵¹ Cost of technology has annually been between \$48/ha and \$99.5/ha, based on estimated share of the trait largely sold as a stacked trait, insecticide cost savings between \$9/ha and \$121/ha and net impact on costs have been between -\$40/ha and + \$48/ha (derived from and based on Traxler et al (2001) and updated from industry sources)

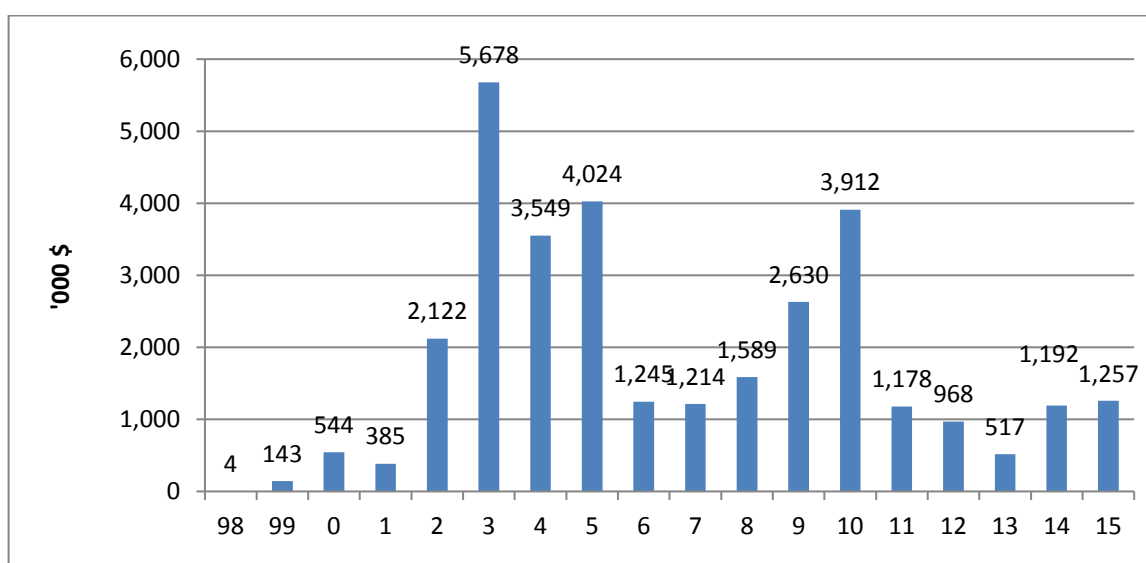
3.8.6 South Africa

In 2015, GM IR cotton⁵² was planted on all of the 9,100 ha cotton crop in South Africa.

The main impact on farm income has been significantly higher yields (an annual average increase of about 24%). In terms of cost of production, the additional cost of the technology (between \$17/ha and \$24/ha for Bollgard I and \$30/ha to \$50/ha for Bollgard II (2006 onwards)) has been greater than the insecticide cost and labour (for water collection and spraying) savings (\$12/ha to \$23/ha), resulting in an increase in overall cost of production of \$2/ha to \$32/ha. Combining the positive yield effect and the increase in cost of production, the net effect on profitability has been an annual increase of between \$27/ha and \$507/ha.

At the national level, farm incomes over the last five years have annually increased by between \$0.5 million and \$3.9 million (Figure 13). Cumulatively since 1998, the farm income benefit has been \$32.1 million.

Figure 13: National farm income impact: GM IR cotton in South Africa 1998-2014 (million \$)



Sources and notes:

1. Impact data based on Ismael et al (2002)
2. Yield impact +24%, cost of technology \$14/ha-\$24/ha for Bollgard I and \$30/ha-\$50/ha for Bollgard II, cost savings (reduced insecticide use) \$12/ha-\$23/ha
3. All values for prices and costs denominated in South African Rand have been converted to US dollars at the annual average exchange rate in each year
4. The decline in the total farm income benefit 2004 and 2005 relative to earlier years reflects the decline in total cotton plantings. This was caused by relatively low farm level prices for cotton in 2004 and 2005 (reflecting a combination of relatively low world prices and a strong South African currency)

3.8.7 India

GM IR cotton has been planted commercially in India since 2002. In 2015, 11.3 million ha were planted to GM IR cotton which is equal to 95% of total plantings.

⁵² First planted commercially in 1998

The main impact of using GM IR cotton has been major increases in yield⁵³. With respect to cost of production, the average cost of the technology (seed premium: \$49/ha to \$54/ha) up to 2006 was greater than the average insecticide cost savings of \$31/ha-\$58/ha resulting in a net increase in costs of production. Following the reduction in the seed premium in 2006 to \$12/ha-\$20/ha, farmers have made a net cost saving of \$16/ha-\$25/ha. Coupled with the yield gains, important net gains to levels of profitability have been achieved of between \$82/ha and \$356/ha. At the national level, the farm income gain in 2015 was \$1.33 billion and cumulatively since 2002 the farm income gains have been \$19.6 billion (Table 32).

Table 32: Farm level income impact of using GM IR cotton in India 2002-2015

Year	Cost savings (net after cost of technology: \$/ha)	Net increase in gross margins (\$/ha)	Increase in farm income at a national level (\$ millions)
2002	-12.42	82.66	3.69
2003	-16.2	209.85	20.98
2004	-13.56	193.36	96.68
2005	-22.25	255.96	332.74
2006	3.52	221.02	839.89
2007	26.41	356.85	2,093.97
2008	24.28	256.73	1,790.16
2009	22.19	211.17	1,754.96
2010	23.10	265.80	2,498.53
2011	22.64	287.07	3,056.76
2012	19.77	198.29	2,141.58
2013	18.03	191.57	2,107.29
2014	17.31	137.29	1,604.05
2015	16.47	117.67	1,330.30

Sources and notes:

1. Impact data based on Bennett et al (2004), IMRB (2005 & 2007), Gruere (2008), Qaim (2009), Herring and Rao (2012)
2. All values for prices and costs denominated in Indian Rupees have been converted to US dollars at the annual average exchange rate in each year

The impact on total cotton production was an increase of 22.1% in 2015.

3.8.8 Brazil

GM IR cotton was planted commercially in Brazil for the first time in 2006, and in 2015 was planted on 477,000 ha (50% of the total crop). The area planted to GM IR cotton in Brazil has fluctuated (eg, 358,000 ha in 2007 and 116,000 ha in 2009) largely due to the performance of the seed containing the GM IR trait compared to leading conventional varieties. In 2006, on the basis of industry estimates of impact of GM IR cotton relative to similar varieties (average yield gain of +6% and a net cost saving from reduced expenditure on insecticides after deduction of the premium paid for using the technology of about +\$25/ha), a net farm income gain of about \$125/ha was realised. Since then, however, improved conventional varieties in which the GM IR

⁵³ Bennett et al (2004) found average yield increases of 45% in 2002 and 63% in 2003 (average over the two years of 54%) relative to conventionally produced cotton. Survey data from Monsanto (2005) confirmed this high yield impact (+58% reported in 2004) and from IMRB (2006) which found an average yield increase of 64% in 2005 & IMRB (2007) which found a yield impact of +50% in 2006. Later work by Gruere (2008), Qaim (2009) and Herring and Rao (2012) have all confirmed significant yield increases in the range of +30% to +40%

trait is not present have dominated production because of their superior yields. As a result, varieties containing the GM IR trait have delivered inferior yields (despite offering effective control against bollworm pests) relative to the leading conventional varieties. In addition, boll weevil is a major pest in many cotton growing areas, a pest that the GM IR technology does not target. Analysis by Galvao (2009 & 2010) estimated that the yield performance of the varieties containing GM IR traits was lower (by -2.7% to -3.8%) than the leading conventional alternatives available in 2007-2009. As a result, the average impact on farm income (after taking into consideration insecticide cost savings and the seed premium) has been negative (-\$34.5/ha in 2007, a small net gain of about \$2/ha in 2008 and a net loss of -\$44/ha in 2009). Not surprisingly, at the country level, this resulted in net aggregate losses in 2007 and 2009 from using the technology (eg, -\$5 million in 2009). In 2010, stacked traits (containing GM HT and GM IR traits) became available in some of the leading varieties for the first time and this has contributed to the increase in plantings since 2010. Annual estimates of the impact of this technology (Galvao (2010-2015)) found average yield impacts of zero in 2010, +3% in 2011, -1.8% in 2012 and +2.4% 2013-2015 relative to the best performing conventional varieties. Based on these yield finding, seed premia of \$42.54/ha 2010, \$52.3/ha 2011, \$34.08/ha 2012, \$43.99/ha 2013, \$40.3/ha 2014, \$26/ha 2015 and insecticide cost savings of \$58.94/ha 2010, \$42.7/ha 2011, \$41.4/ha 2012, \$37.5/ha 2013, \$58.7/ha 2014 and \$35/ha 2015, the net impact from using the GM IR technology was +\$58.6/ha in 2015. At the national level this equates to a net income gain of \$28 million. Cumulatively, since 2006 GM IR technology has delivered an aggregate net farm income gain of \$100.65 million.

3.8.9 Other countries

- Colombia.** GM IR cotton has been grown commercially in Colombia since 2002 (15,040 ha planted in 2015 out of a total cotton crop of 20,000 ha). Drawing on recent analysis of impact by Zambrano et al (2009), the main impact has been a significant improvement in yield (+32%). On the cost side, this analysis shows that GM IR cotton farmers tend to have substantially higher expenditures on pest control than their conventional counterparts which, when taking into consideration the approximate \$70/ha cost of the technology, results in a net addition to costs of between \$200/ha and \$280/ha (relative to typical expenditures by conventional cotton growers). Nevertheless, after taking into consideration the positive yield effects, the net impact on profitability has been positive. In 2008, the average improvement in profitability was about \$90/ha and the total net gain from using the technology was \$1.8 million⁵⁴. Since the Zambrano work, the use of GM IR cotton has seen problems with reduced yield benefits in 2009 due mainly to heavy rains in the planting season delaying planting, followed by lack of rain in the growing season and the increasing availability of stacked trait seed. For the purposes of this analysis, from 2010 estimates of impact are based on industry source data which were a net yield benefit of +10%, seed premium of \$104/ha-\$171/ha and insecticide cost savings of \$50/ha to \$87/ha. As a result, the net farm income benefit in 2015 was estimated to be +\$115/ha. At the national level, this equated to a net farm income gain of \$1.72 million. Cumulatively, since 2002 the net farm income gain was \$20.76 million;

⁵⁴ Given that the Zambrano et al work identified important differences between the baseline level of insecticide use by GM IR cotton users and conventional cotton farmers (pre-adoption of the technology), this probably understates the cost savings associated with the technology. A more representative assessment of the impact compares the costs (post adoption) of GM IR technology users with the likely costs of reverting back to conventional technology on these farms

- *Burkina Faso*: GM IR cotton was first grown commercially in 2008. In 2015, GM IR cotton accounted for 50% (330,000 ha) of total plantings. Based on analysis by Vitale et al (2006, 2008 and 2009), the main impact of the technology is improved yields (by +18% to +20%) and savings in insecticide expenditure of about \$52/ha. Based on a cost of technology of \$53/ha, the net impact on cost of production is marginally negative, but inclusive of the yield gains, the net income gain in 2015 was \$81.9/ha. The total aggregate farm income gain, in 2015 was \$27 million and cumulatively, since 2008, it has been \$204.6 million;
- *Pakistan*: After widespread 'illegal' planting of GM IR cotton in Pakistan for several years, it was officially permitted in 2009 and in 2015, 93% of the crop (2.72 million ha) used this technology. Initial analysis of the impact draws on Nazli et al (2010) which identified an average yield gain of +12.6%, seed premium of about \$14/ha-\$15/ha and an average insecticide cost saving of about \$20/ha. Based on this analysis (undertaken during a period when unofficial and largely illegal seed was used), the average farm income benefit in 2009 was \$37/ha. Subsequent analysis by Kouser and Qaim (2013) has formed the basis of our estimates for impacts from 2010. This is based on a yield benefit of +22%, a technology (seed) premium of about \$4-\$5/ha and crop protection savings of \$10-\$12/ha. For 2015, the estimated average farm income benefit was \$146.6/ha. At the national level this is equal to a net farm income gain of \$398 million. Cumulatively since 2009, the farm income benefit of using this technology is \$4.31 billion;
- *Myanmar*: GM IR cotton has been grown in Myanmar since 2007 and in 2015, 223,000 ha (93% of the total crop) used seed containing the trait. Data on the impact of the technology in Myanmar is limited, with the brief report from the USDA (2011) being the only one identified. This indicated that the technology has been used exclusively in 'long staple' varieties and was delivering up to a 70% improvement in yield (source: extension advisors). Given 'long staple' varieties account for only a part of the total crop, our analysis uses a more conservative average yield of +30% and applies this only to the 'long staple' area (estimates thereof). In addition, due to the lack of data on seed premia and cost savings (relating to labour and insecticide use), we have used data based on costs and impacts from India. Based on these assumptions, the average income gain in 2015 was \$210/ha, which at the national level amounts to a gain of \$47 million. Cumulatively the farm income gain since 2007 has been \$307.9 million;
- *Sudan and Paraguay*: These countries have respectively been using GM IR cotton since 2012 and 2013. No detailed impact analysis has been identified for the technology in these countries.

3.8.10 Summary of global impact

In global terms, the farm level impact of using GM IR cotton was \$3.27 billion in 2015. Cumulatively since 1996, the farm income benefit has been (in nominal terms) \$50.27 billion. Within this, 81% of the farm income gain has derived from yield gains (less pest damage) and the balance (19%) from reduced expenditure on crop protection (spraying of insecticides).

In terms of the total value of cotton production from the countries growing GM IR in 2015, the additional farm income generated by the technology is equal to a value-added equivalent of 13.5%. Relative to the value of global cotton production in 2015, the farm income benefit added the equivalent of 9.6%.

3.9 Other GM crops

3.9.1 Maize/corn rootworm resistance

GM IR (resistant to corn rootworm (CRW)) maize has been planted commercially in the US since 2003. In 2015, there were 15.8 million ha of GM IR CRW maize (48% of the total US crop).

The main farm income impact⁵⁵ has been higher yields of about 5% relative to conventional maize. The impact on average costs of production has been +\$2/ha to +\$12/ha (based on an average cost of the technology of \$25/ha-\$42/ha and an insecticide cost saving of \$23/ha-\$37/ha⁵⁶). As a result, the net impact on farm profitability has been +\$24/ha to +\$102/ha.

At the national level, farm incomes increased by \$1.05 billion in 2015. Cumulatively since 2003, the total farm income gain from the use of GM IR CRW technology in the US maize crop has been +\$12.18 billion.

GM IR CRW cultivars were also planted commercially for the first time in 2004 in Canada. In 2015, the area planted to CRW resistant varieties was 0.69 million ha. Based on US costs, insecticide cost savings and yield impacts, this has resulted in additional income at the national level of \$53.1 million in 2015 (cumulative total since 2004 of \$372.7 million).

At the global level, the extra farm income derived from GM IR CRW maize use has been \$12.56 billion.

3.9.2 Virus resistant papaya

Ringspot resistant papaya has been commercially grown in the US (State of Hawaii) since 1999, and in 2015, 75% of the state's papaya crop was GM virus resistant (455 ha of fruit bearing trees).

The main farm income impact of this technology has been to significantly increase yields relative to conventional varieties. Compared to the average yield in the last year before the first biotech cultivation (1998), the annual average yield increase of biotech papaya relative to conventional crops has been within a range of +15% to +77% (17% in 2015). At a state level, this was equivalent to a 12.75% increase in total papaya production.

In terms of profitability⁵⁷, the net annual impact has been an improvement of between \$2,400/ha and \$11,400/ha, and in 2015, this amounted to a net farm income gain of \$3,096/ha and an aggregate benefit across the state of \$1.41 million. Cumulatively, the farm income benefit since 1999 has been \$27.9 million.

Virus resistant papaya are also reported to have been grown in China, (7,000 ha in 2015). No impact data on this technology has been identified.

⁵⁵ Impact data based on Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006), Johnson and Strom (2008) and Rice (2004)

⁵⁶ The average area on which the insecticide cost savings have been applied has been limited to the historic area typically treated with insecticides for rootworm pests (about 40% of the total crop). In addition, from 2012, the area on which this saving has been applied has been reduced to reflect increased spraying with insecticides that target rootworm pests by some farmers who perceive they may have problems with rootworm developing resistance to the IR technology

⁵⁷ Impact data based on Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006) and Johnson and Strom (2008)

3.9.3 Virus resistant squash

GM virus resistant squash has also been grown in some states of the US since 2004. It is estimated to have been planted on 1,000 ha in 2015⁵⁸ (6% of the total crop).

Based on analysis from Johnson & Strom (2008), the primary farm income impact of using GM virus resistant squash has been derived from higher yields which in 2015, added a net gain to users of \$10.4 million. Cumulatively, the farm income benefit since 2004 has been \$278.8 million.

3.9.4 Other crops

a) Potatoes

GM IR potatoes were grown commercially in the US between 1996 and 2000 (planted on 4% of the total US potato crop in 1999 (30,000 ha)). This technology was withdrawn in 2001 when the technology provider (Monsanto) withdrew from the market to concentrate on GM trait development in maize, soybeans, cotton and canola. This commercial decision was also probably influenced by the decision of some leading potato processors and fast food outlets to stop using GM potatoes because of perceived concerns about this issue from some of their consumers, even though the GM potato provided the producer and processor with a lower cost, higher yielding and more consistent product. It also delivered significant reductions in insecticide use (Carpenter & Gianessi (2002)).

High starch potatoes were also approved for planting in the EU in 2010 and a small area was planted in member states such as Sweden, the Czech Republic and Germany until the technology provider withdrew the product from the market in 2012. There is no data available on the impact of this technology.

b) Alfalfa

GM HT alfalfa was first commercialised in the US in 2007 on about 100,000 ha. However, between 2008 and 2010, it was not allowed to be planted due to legal action requiring the completion of additional environmental impact assessments. This was completed by 2010 and commercial use of the technology allowed to be resumed in 2011. Approximately 1.3 million ha of GM alfalfa were being cropped in 2015. The technology is reported to offer improved weed control, better yields and higher quality forage. No analysis is presented here due to the lack of published studies on the impact.

3.10 Indirect (non-pecuniary) farm level economic impacts

As well as the tangible and quantifiable impacts identified and analysed on farm profitability presented above, there are other important impacts of an economic nature. These include impacts on a broader range of topics such as labour use, households and local communities. The literature on these impacts is developing and a full examination of these impacts potentially merits a study in its own right. These issues are not examined in depth in this work as to do so would add considerably to an, already, long report. As such, this section provides only a summary of some of the most important additional, and mostly intangible, difficult to quantify, impacts.

⁵⁸ Mostly found in Georgia and Florida

Many of the impact studies⁵⁹ cited in this report have identified the following reasons as being important influences for adoption of the technology:

Herbicide tolerant crops

- Increased management flexibility and convenience that comes from a combination of the ease of use associated with broad-spectrum, post emergent herbicides like glyphosate and the increased/longer time window for spraying. This not only frees up management time for other farming activities but also allows additional scope for undertaking off-farm, income earning activities;
- In a conventional crop, post-emergent weed control is important and relies on herbicide applications after the weeds and crop are established. As a result, the crop may suffer 'knock-back' to its growth from the effects of the herbicide. In the GM HT crop, this problem is avoided because the crop is tolerant to the herbicide;
- Facilitates the adoption of conservation or no tillage systems. This provides for additional cost savings such as reduced labour and fuel costs associated with ploughing, additional moisture retention and reductions in levels of soil erosion;
- Improved weed control has contributed to reduced harvesting costs – cleaner crops have resulted in reduced times for harvesting and improved harvest quality which in some cases has led to price bonuses;
- Elimination of potential damage caused by soil-incorporated residual herbicides in current crops and follow-on crops (eg, TT canola in Australia). This also means less need to apply herbicides post-emergence and in a follow-on crop because of the improved levels of weed control;
- A contribution to the general improvement in human safety (as manifest in greater peace of mind about own and worker safety) from a switch to more environmentally benign products.

Insect resistant crops

- Production risk management/insurance purposes – the technology takes away much of the worry of significant pest damage occurring and is, therefore, highly valued;
- A 'convenience' benefit derived from having to devote less time to crop walking and/or applying insecticides;
- Savings in energy use – mainly associated with less use of aerial spraying;
- Savings in machinery use (for spraying and possibly reduced harvesting times);
- Higher quality of crop. There is a growing body of research evidence relating to the superior quality of GM IR corn relative to conventional and organic corn from the perspective of having lower levels of mycotoxins;
- Improved health and safety for farmers and farm workers (from reduced handling and use of pesticides, especially in developing countries where many apply pesticides with little or no use of protective clothing and equipment);
- Shorter growing season (eg, for some cotton growers in India) which allows some farmers to plant a second crop in the same season⁶⁰. Also some Indian cotton growers

⁵⁹ For example, relating to HT soybeans; USDA (1999), Gianessi & Carpenter (2000), Qaim & Traxler (2002), Brookes (2008); relating to insect resistant maize, Rice (2004); relating to insect resistant cotton Ismael et al (2002), Pray et al (2002)

⁶⁰ Notably maize in India

have reported knock on benefits for bee keepers as fewer bees are now lost to insecticide spraying.

Since the early 2000s, a number of farmer-survey based studies in the US have also attempted to better quantify these non pecuniary benefits. These studies have usually employed contingent valuation techniques⁶¹ to obtain farmers' valuations of non pecuniary benefits. A summary of these findings is shown in Table 33.

Table 33: Values of non-pecuniary benefits associated with GM crops in the US

Survey	Median value (\$/hectare)
2002 IR (to rootworm) corn growers survey	7.41
2002 soybean (HT) farmers survey	12.35
2003 HT cropping survey (corn, cotton & soybeans) – North Carolina	24.71
2006 HT (flex) cotton survey	12.35 (relative to first generation HT cotton)

Source: Marra & Piggot (2006) and (2007)

Aggregating the impact to US crops 1996-2015

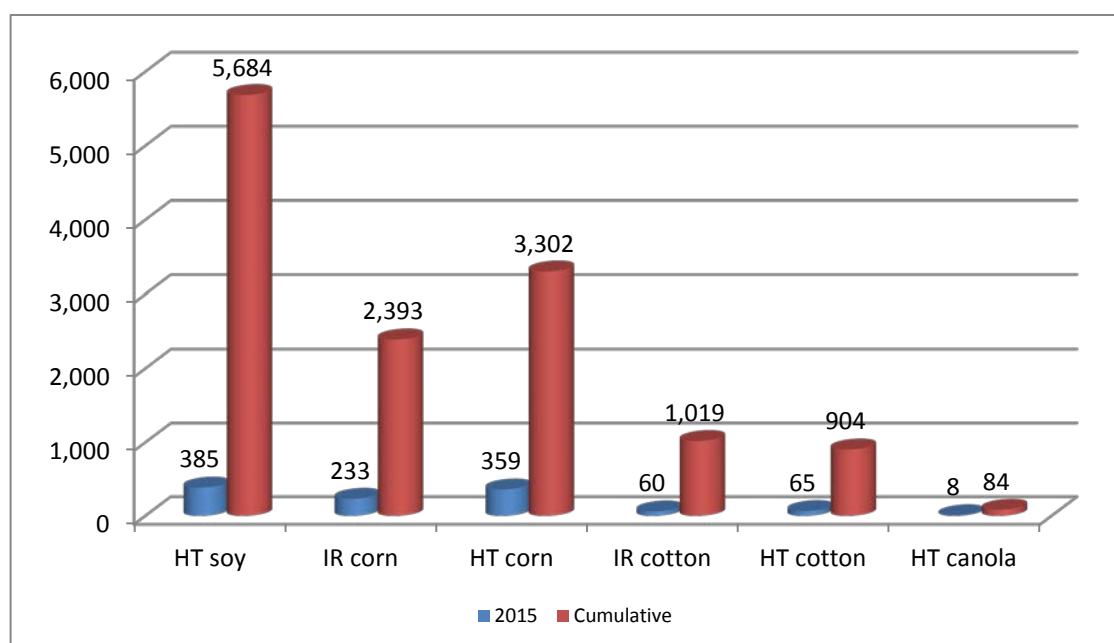
The approach used to estimate the non-pecuniary benefits derived by US farmers from biotech crops over the period 1996-2015 has been to draw on the values identified by Marra and Piggot (2006 & 2007: Table 33) and to apply these to the GM crop planted areas in this period.

Figure 14 summarises the values for non-pecuniary benefits derived from GM crops in the US and shows an estimated (nominal value) benefit of \$1.11 billion in 2015 and a cumulative total benefit (1996-2015) of \$13.38 billion. Relative to the value of direct farm income benefits presented above, the non-pecuniary benefits were equal to 16% of the total direct income benefits in 2015 and 18.4% of the total cumulative (1996-2015) direct farm income. This highlights the important contribution this category of benefit has had on biotech trait adoption levels in the US, especially where the direct farm income benefits have been identified to be relatively small (eg, HT cotton).

Estimating the impact in other countries

It is evident from the literature review that GM technology-using farmers in other countries also value the technology for a variety of non-pecuniary/intangible reasons. The most appropriate methodology for identifying these non pecuniary benefit valuations in other countries would be to repeat the type of US farmer-surveys in other countries. Unfortunately, the authors are not aware of any such studies having been undertaken to date.

⁶¹ Survey based method of obtaining valuations of non market goods that aims to identify willingness to pay for specific goods (eg, environmental goods, peace of mind, etc) or willingness to pay to avoid something being lost

Figure 14: Non-pecuniary benefits derived by US farmers 1996-2015 by trait (\$ million)

3.11 Production effects of the technology

Based on the yield assumptions used in the direct farm income benefit calculations presented above (see Appendix 1) and taking into account the second soybean crop facilitation in South America, GM crops have added important volumes to global production of maize, cotton, canola and soybeans (Table 34).

Table 34: Additional crop production arising from positive yield effects of GM crops

	1996-2015 additional production (million tonnes)	2015 additional production (million tonnes)
Soybeans	180.26	21.89
Corn	357.75	40.28
Cotton	25.20	2.19
Canola	10.64	1.44
Sugar beet	1.05	0.15

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

The GM IR traits, used in maize and cotton, have accounted for 94.3% 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 Australia⁶²) 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 20 years since 1996 has been +13.1% for maize and +15% for cotton (Table 35).

⁶² This reflects the levels of *Heliothis* and *Helicoverpa* (boll and bud worm) pest control previously obtained with intensive insecticide use. The main benefit and reason for adoption of this technology in Australia has arisen from significant cost savings (on insecticides) and the associated environmental gains from reduced insecticide use

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 148 million tonnes to soybean production in Argentina and Paraguay between 1996 and 2015 (accounting for 84.9% of the total GM-related additional soybean production).

Table 35: Average (%) yield gains GM IR cotton and maize 1996-2015

	Maize insect resistance to corn boring pests	Maize insect resistance to rootworm pests	Cotton insect resistance
US	7.0	5.0	9.9
China	N/a	N/a	10.0
South Africa	11.2	N/a	24.0
Honduras	23.8	N/a	N/a
Mexico	N/a	N/a	11.0
Argentina	6.1	N/a	30.0
Philippines	21.2	N/a	N/a
Spain	11.1	N/a	N/a
Uruguay	5.6	N/a	N/a
India	N/a	N/a	31.0
Colombia	21.7	N/a	18.0
Canada	7.0	5.0	N/a
Burkina Faso	N/a	N/a	18.0
Brazil	11.9	N/a	0.8
Pakistan	N/a	N/a	21.0
Myanmar	N/a	N/a	30.9
Australia	N/a	N/a	Nil
Paraguay	5.5	N/a	Not available

Notes: N/a = not applicable

3.12 Trade flows and related issues

a) Share of global exports

Looking at the extent to which the leading GM producing countries are traders (exporters) of these crops and key derivatives (Table 36 and Table 37) show the following:

- *Soybeans*: in 2015/16, 42% of global production was exported and 97.7% of this trade came from countries which grow GM soybeans. As there has been some development of a market for certified conventional soybeans and derivatives (mostly in the EU, Japan and South Korea), this has necessitated some segregation of (certified) non GM/conventional exports from supplies that may contain GM origin material, or sourcing from countries where GM HT soybeans are not grown. Based on estimates of the size of the certified non GM/conventional soy markets in the EU and SE Asia (the main markets)⁶³, between

⁶³ Brookes (2008b) and updated from industry sources and own research

2.3% and 3.6% of global trade in soybeans is probably required to be certified as conventional. A similar pattern occurs in soymeal, where 88%-91% of globally traded meal probably contains GM material;

- *Maize*: 15% of global production was internationally traded in 2015/16⁶⁴. Within the leading exporting nations, the GM maize growers of the US, Argentina, Brazil, Paraguay, South Africa and Canada are important players (78% of global trade). As there has been some limited development of a distinct market which requires certified conventional maize (mostly in the EU, Japan and South Korea), this has necessitated some segregation of exports into GM versus certified conventional supplies. The likely share of global trade accounted for by GM maize exports is 73%-78%;
- *Cotton*: in 2015/16, 37% of global production was traded internationally. Of the leading exporting nations, the GM cotton growing countries of the US, Australia, India, Pakistan, Brazil and Burkina Faso are prominent exporters accounting for 68% of global trade. Given that the market for certified conventional cotton is very small, virtually all of this share of global cotton trade from GM cotton growing countries is probably not subject to any form of segregation and hence may contain GM derived material⁶⁵. In terms of cottonseed-meal the GM share of global trade is 50%;
- *Canola*: 21% of global canola production in 2015/16 was exported, with Canada being the main global trading country. The share of global canola exports accounted for by the three GM HT canola producing countries (Canada, the US and Australia) was 86% in 2015/16. As there has been only a very small development of a market for certified conventional canola globally (the EU, the main market where certified conventional products are required, has been largely self-sufficient in canola and does not currently grow GM canola), non-segregated GM exports probably account for 85%-86% of global trade. For canola/rapemeal, the GM share of global trade is about 73%.

Table 36: Share of global crop trade accounted for GM production 2015/16 (million tonnes)

	Soybeans	Maize	Cotton	Canola
Global production	313.0	960.7	21.0	70.2
Global trade (exports)	132.3	144.9	7.7	14.7
Share of global trade from GM producers	129.2 (98%)	113.5 (78%)	5.23 (68%)	12.7 (86%)
Estimated size of market requiring certified conventional (in countries that have import requirements)	3.0-3.5	7.0	Negligible	0.1
Estimated share of global trade that may contain GM (ie, not required to be segregated)	125.7-129.2	106.5-113.5	5.23	12.6-12.7
Share of global trade that may be GM	95% to 97.7%	73.5%-78.3%	68%	85.7% to 86.4%

Sources: derived from and updated - USDA & Oil World statistics, Brookes (2008b)

⁶⁴ Maize is an important subsistence crop in many parts of the world and hence the majority of production is consumed within the country of production

⁶⁵ We consider this to be a reasonable assumption; we are not aware of any significant development of a certified conventional versus biotech cotton market and hence there is little evidence of any active segregation of exports

Notes: Estimated size of market requiring certified conventional in countries with import requirements excludes countries with markets for certified conventional for which all requirements are satisfied by domestic production (eg, maize in the EU). Estimated size of certified conventional market for soybeans (based primarily on demand for derivatives used mostly in the food industry): main markets - EU 2.25-2.75 million tonnes bean equivalents, Japan and South Korea 0.75 million tonnes

Table 37: Share of global crop derivative (meal) trade accounted for GM production 2015/16 (million tonnes)

	Soymeal	Cottonseed meal	Canola/rape meal
Global production	216.75	13.55	39.23
Global trade (exports)	65.6	0.30	5.63
Share of global trade from GM producers	59.8 (91%)	0.15 (50%)	4.1 (73%)
Estimated size of market requiring certified conventional (in countries that have import requirements)	1.6-2.0	Negligible	Negligible
Estimated share of global trade that may contain GM (ie, not required to be segregated)	57.8-59.8	0.15	4.1
Share of global trade that may be GM	88.1%-91.1%	50%	73%

Sources: derived from and updated - USDA & Oil World statistics, Brookes (2008b)

Notes: Estimated size of certified conventional market for soymeal: EU 1.5-1.9 million tonnes, Japan and South Korea 0.1 million tonnes (derived largely from certified conventional beans referred to in above table)

4 The environmental impact of GM crops

This section examines the environmental impact of using GM crops over the last twenty years. The two key aspects of environmental impact explored are:

- a. Impact on insecticide and herbicide use.
- b. Impact on carbon emissions.

These are presented in the sub-sections below.

4.1 Use of insecticides and herbicides

Assessment of the impact of GM crops on insecticide and herbicide use requires comparisons of the respective weed and pest control measures used on GM versus the 'conventional alternative' form of production. This presents a number of challenges relating to availability and representativeness.

Comparison data ideally derives from farm level surveys which collect usage data on the different forms of production. A search of the literature on insecticide or herbicide use change with GM crops shows that the number of studies exploring these issues is limited with even fewer providing data to the pesticide (active ingredient) level. Secondly, national level pesticide usage survey data is also extremely limited; there are no published, detailed, annual pesticide usage surveys conducted by national authorities in any of the countries currently growing GM crop traits. The only country in which pesticide usage data is collected (by private market research companies) on an annual basis, and which allows a comparison between GM and conventional crops to be made, is the US⁶⁶.

Even where national pesticide use survey data is available, it has limitations. A reasonable estimate of the amount of herbicide or insecticide usage changes that have occurred with GM crop technology, requires an assessment of what herbicides/insecticides might reasonably be expected to be used in the absence of crop biotechnology on the relevant crops (ie, if the entire crops used non GM production methods). Applying usage rates for the current (remaining) conventional crops is one approach. However, if this conventional cropping data set relates to a relatively small share of total crop area (as it does in the case of a number of crops and countries where GM technology has been adopted), it will likely produce biased and unrepresentative information about the levels of herbicide or insecticide use that might reasonably be expected across the whole crop in the absence of GM technology because:

- Whilst the degree of pest/weed problems/damage vary by year, region and within region, farmers who continue to farm conventionally may be those with relatively low levels of pest/weed problems, and hence see little, if any, economic benefit from using the GM traits targeted at minimal pest/weed problems. Their insecticide/herbicide usage levels therefore tend to be below the levels that would reasonably be expected on an average farm with more typical pest/weed infestations;

⁶⁶ The US Department of Agriculture also conducts pesticide usage surveys but these are not conducted on an annual basis (eg, the last time maize was included was 2010 and previous to this in 2005) and do not disaggregate usage by production type (GM versus conventional)

- Some of the farms continuing to use conventional seed generally use extensive, low intensity production methods (including organic) which feature limited (below average) use of herbicides/insecticides. The usage patterns of this sub-set of growers is therefore likely to understate usage for the majority of farmers if they all returned to farming without the use of GM technology;
- The widespread adoption of GM IR technology has resulted in 'area-wide' suppression of target pests such as stalk borers in maize crops. As a result, conventional farmers (eg, of maize in the US) have benefited from this lower level of pest infestation and the associated reduced need to conduct insecticide treatments;
- Some of the farmers using GM traits have experienced improvements in pest/weed control from using this technology relative to the conventional control methods previously used. If these farmers were to now revert to using conventional techniques, it is likely that most would wish to maintain the levels of pest/weed control delivered with use of the GM traits and therefore some would use higher levels of insecticide/herbicide than they did in the pre GM crop days. This argument can, however, be countered by the constraining influence on farm level pesticide usage that comes from the cost of pesticides and their application. Ultimately the decision to use more pesticide or not would be made at the farm level according to individual assessment of the potential benefits (from higher yields) compared to the cost of additional pesticide use.

This problem of bias and poor representativeness of pesticide usage data obtained from a small conventional data set (for what might reasonably be considered as the 'conventional alternative' if GM technology was not available) has been addressed in this report in the following ways:

- Firstly, by using the average recorded values for insecticide/herbicide usage on conventional crops for years only when the conventional crop accounted for the majority (50% or more) of the total crop and;
- Secondly, in other years (eg, from 1999 for soybeans, from 2001 for cotton and from 2007 for maize in the US) applying estimates of the likely usage if the whole US crop was no longer using crop biotechnology, based on opinion from extension and industry advisors across the US as to what farmers might reasonably be expected to use in terms of weed control practices and usage levels of insecticide/herbicide. In addition, the usage levels identified from this methodology were cross checked (and subject to adjustment) against historic average usage levels of key herbicide and insecticide active ingredients from the private market research data set so as to minimise the scope for understating or overstating likely usage levels on the conventional alternative.

Overall, this approach has been applied in other countries where pesticide usage data is available, though more commonly, because of the paucity of available data, the analysis relies more on extension/advisor opinion and knowledge of actual and potential pesticide use.

This methodology has been used by others. It also has the advantage of providing comparisons of current crop protection practices on both GM crops and the conventional alternatives, so takes into account dynamic changes in crop protection management practices and technologies, rather than making comparisons solely on past practices. Details of how this methodology has been applied to the 2015 calculations, sources used for each trait/country combination examined and examples of typical conventional versus GM pesticide applications are provided in Appendix 3.

The most common way in which environmental impact associated with pesticide use changes with GM crops (and with the adoption of other production systems) has typically been presented in the literature has been in terms of the volume (quantity) of pesticide applied. However, whilst the amount of pesticide applied to a crop is one way of trying to measure the environmental impact of pesticide use, this is not a good measure of environmental impact because the toxicity and risk of each pesticide is not directly related to the amount (weight) applied. For example, the environmental impact of applying one kg of dioxin to a crop or land is far more toxic than applying 1 kg of salt. There exist alternative (and better) measures that have been used by a number of authors of peer reviewed papers to assess the environmental impact of pesticide use change with GM crops rather than simply looking at changes in the volume of active ingredient applied to crops. In particular, there are a number of peer reviewed papers that utilise the Environmental Impact Quotient (EIQ) developed at Cornell University by Kovach et al (1992) and updated annually. This integrates the various environmental impacts of individual pesticides (eg, on farm workers, consumers, ecology: see Appendix 4 for additional information) into a single 'field value per hectare'. The EIQ value is multiplied by the amount of pesticide active ingredient (ai) used per hectare to produce a field EIQ value. For example, the EIQ rating for glyphosate is 15.33. By using this rating multiplied by the amount of glyphosate used per hectare (eg, a hypothetical example of 1.1 kg applied per ha), the field EIQ value for glyphosate would be equivalent to 16.86/ha. The EIQ indicator used is therefore a comparison of the field EIQ/ha for conventional versus GM crop production systems, with the total environmental impact or load of each system, a direct function of respective field EIQ/ha values and the area planted to each type of production (GM versus conventional). The use of environmental indicators is commonly used by researchers and the EIQ indicator has been, for example, cited by Brimner et al (2004), in a study comparing the environmental impacts of GM and conventional canola, and by Kleiter et al (2005). The authors of this analysis have also used the EIQ indicator now for several years because it:

- Summarises significant amounts of information on pesticide impact into a single value that, with data on usage rates (amount of active used per hectare) can be readily used to make comparisons between different production systems across many regions and countries;
- Provides an improved assessment of the impact of GM crops on the environment when compared to only examining changes in volume of active ingredient applied, because it draws on some of the key toxicity and environmental exposure data related to individual products, as applicable to impacts on farm workers, consumers and ecology.

The authors, do, however acknowledge that the EIQ is only a hazard indicator and has important weaknesses (see for example, Peterson R and Schleier J (2014) and Kniss A and Coburn C (2015)). It is a hazard rating indicator that does not assess risk or probability of exposure to pesticides. It also relies on qualitative assumptions for the scaling and weighting of (quantitative) risk information that can result, for example, in a low risk rating for one factor (eg, impact on farm workers) may cancel out a high risk rating factor for another factor (eg, impact on ecology). Fundamentally, assessing the full environmental impact of pesticide use changes with different production systems is complex and requires an evaluation of risk exposure to pesticides at a site specific level. This requires substantial collection of (site-specific) data (eg, on ground water levels, soil structure) and/or the application of standard scenario models for exposure in a number of locations. Undertaking such an exercise at a global level would require a substantial

and ongoing input of labour and time, if comprehensive environmental impact of pesticide change analysis is to be completed. It is not surprising that no such exercise has, to date been undertaken, or likely to be in the near future.

Despite the acknowledged weaknesses of the EIQ as an indicator of pesticide environmental impact, the authors of this paper continue to use the EIQ as an indicator of the environmental impact of pesticide use change with GM crops because it is, in our view, a superior indicator to only using amount of pesticide active ingredient applied and can be relatively easily replicated across countries to facilitate comparisons. In this paper, the EIQ indicator is used in conjunction with examining changes in the volume of pesticide active ingredient applied.

Detailed examples of the relevant amounts of active ingredient used and their associated field EIQ values for GM versus conventional crops for the year 2015 are presented in Appendix 3.

4.1.1 GM herbicide tolerant (to glyphosate) soybeans (GM HT)

a) The USA

In examining the impact on herbicide usage in the US, two main sources of information have been drawn on: USDA (NASS) national pesticide usage data and GfK Kynetec (GfK: private market research sector) national farm survey-based pesticide usage data. Based on these sources of information, the main features relating to herbicide usage on US soybeans over the last 20 years have been (Table 38 and Table 39):

- The average amount of herbicide active ingredient (ai) used per hectare on the US soybean crop has been fairly stable for the period to 2006, but has increased since then;
- The average field EIQ/ha load has followed a broadly similar pattern of change as the amount of active ingredient used, although the rate of increase in recent years has been less significant than the rate of increase in active ingredient use;
- A comparison of conventionally grown soybeans (per ha) with GM HT soybeans (Table 39) shows that herbicide ai use on conventional soybeans has also followed a similar pattern of change to GM HT soybeans. Initially usage was fairly stable (at around 1.1 to 1.3kg/ha compared to 1.3 to 1.4kg/ha for GM HT soybeans). Since 2006, the average amount of herbicide active ingredient applied to conventional soybeans has followed the same upward path as usage on GM HT soybeans. The increased usage of herbicides on GM HT soybeans partly reflects the increasing incidence of weed resistance to glyphosate that has occurred in recent years (see section 4.1.9 for additional discussion). 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. In addition, the facilitating role of the technology in the adoption of no and reduced tillage production techniques has also probably contributed to the emergence of weeds resistant to herbicides like glyphosate and to weed shifts towards those weed species that are inherently not well controlled by glyphosate. Some of the glyphosate resistant species, such as marestail (*Conyza canadensis*), waterhemp (*Amaranthus tuberculatus*) and palmer pigweed (*Amaranthus palmeri*) are now widespread in the US.

Growers of GM HT crops in the US are increasingly being advised to be more proactive and include other herbicides (with different and complementary modes of action) in combination with glyphosate (and in some cases reverting back to ploughing) in their integrated weed management systems, even where instances of weed resistance to glyphosate have not been found.

This proactive, diversified approach to weed management is therefore the principal strategy for avoiding the emergence of herbicide resistant weeds in GM HT crops. A proactive weed management programme generally requires less herbicide, has a better environmental profile and is more economical than a reactive weed management programme.

At the macro level, the adoption of both reactive and proactive weed management programmes in GM HT crops has influenced the mix, total amount and overall environmental profile of herbicides applied to GM HT soybeans (and to cotton, corn and canola) in the last 10 years. This is shown in the evidence relating to changes in herbicide use, as illustrated in Table 38 and Table 39. Thus, in 2015, 80% of the GM HT soybean crop received an additional herbicide treatment of one of the following (four most used, after glyphosate) active ingredients⁶⁷ 2,4-D, chlorimuron, fomesafen and sulfentrazone. This compares with 14% of the GM HT soybean crop receiving a treatment of one of the four most used (after glyphosate) herbicide active ingredients in 2006. As a result, the average amount of herbicide active ingredient applied to the GM HT soybean crop in the US (per hectare) increased by 81% over this period. This compared with the average amount of herbicide active ingredient applied to the small conventional (non GM) soybean alternative which increased by 84% over the same period. The increase in the use of herbicides on conventional soybeans reflects a shift in herbicide use (more herbicides) rather than an increase in dose rates and can therefore be partly attributed to the on-going development of weed resistance to non-glyphosate herbicides commonly used. This highlights that the development of weed resistance to herbicides is a problem faced by all farmers, regardless of production method (also see section 4.1.9 for more detailed discussion of weed resistance issues);

- A comparison of average field EIQs/ha also shows fairly stable values for both conventional and GM HT soybean crops for most of the period to the mid-2000s, followed by increases in the last ten years. The average load rating for GM HT soybean crops has been lower than the average load rating for conventional soybeans for most of the period, 2008-2015 excepted, despite the continued shift to no/low tillage production systems that rely much more on herbicide-based weed control than conventional tillage systems and the adoption of reactive and proactive weed resistance management programmes. Since 2006, the average field EIQ/ha ratings on GM HT soybean and conventional soybean crops have increased significantly on both production systems.

⁶⁷ The four most used herbicide active ingredients used on soybeans after glyphosate (source: derived from GfK)

Table 38: Herbicide usage on soybeans in the US 1996-2015

Year	Average ai use (kg/ha): NASS data	Average ai use: GfK Kynetec data: index 1998=100	Average field EIQ/ha: NASS data	Average field EIQ/ha: based on GfK Kynetec data
1996	1.02	N/a	22.0	N/a
1997	1.22	N/a	26.2	N/a
1998	1.09	100	21.5	25.8
1999	1.05	94.9	19.6	23.2
2000	1.09	96.0	20.2	23.1
2001	0.73	100.1	13.4	23.5
2002	1.23	97.8	21.4	21.6
2003	N/a	104.7	N/a	22.6
2004	1.29	106.1	15.2	22.6
2005	1.23	106.3	20.2	22.6
2006	1.53	101.3	16.9	21.4
2007	N/a	113.0	N/a	23.6
2008	N/a	125.1	N/a	26.1
2009	N/a	125.7	N/a	26.6
2010	N/a	135.0	N/a	28.8
2011	N/a	144.8	N/a	31.3
2012	1.97	160.9	32.0	35.0
2013	N/a	166.1	N/a	35.9
2014	N/a	165.6	N/a	35.9
2015	1.93	179.0	34.5	40.8

Sources: NASS data - no collection of data in 2003, 2007-2011, 2013, 2014. GfK 1998-2015, N/A = not available. Average ai/ha figures derived from GfK dataset are not permitted by GfK to be published

Table 39: Herbicide usage on GM HT and conventional soybeans in the US 1996-2015

Year	Average ai use (kg/ha) index 1998=100: conventional	Average ai use (kg/ha) index 1998=100: GM HT	Average field EIQ/ha: conventional	Average field EIQ/ha: GM HT
1996	93.6	93.6	28.3	22.8
1997	111.9	111.9	34.1	27.2
1998	100	100	28.1	22.2
1999	90.3	97.0	25.7	21.5
2000	86.6	99.2	24.5	22.3
2001	91.6	100.8	26.0	22.7
2002	85.2	97.7	24.2	21.1
2003	83.5	104.5	23.6	22.5
2004	84.2	106.0	23.7	22.5
2005	86.2	105.8	23.7	22.5
2006	79.5	100.0	21.3	21.4
2007	90.5	111.3	24.6	23.5
2008	95.1	122.6	25.3	26.1
2009	94.7	124.1	24.5	26.7
2010	97.3	133.1	26.4	28.9
2011	115.7	142.1	29.6	31.4
2012	142.1	157.1	36.7	34.8

2013	119.3	163.2	29.7	36.4
2014	121.3	162.7	31.7	36.2
2015	160.5	180.4	39.2	40.9

Source: derived from GfK

Notes:

1. N/A = not available
2. Average ai/ha figures derived from GfK dataset are not permitted by GfK to be published
3. 1996 and 1997 estimated based on trend in aggregate usage 1996-1998 from USDA NASS

The comparison data between the GM HT crop and the conventional alternative presented above is, however, of limited value because of bias in respect of the conventional crop usage data. The very small area of conventional crop from which herbicide usage data is obtained means that the data poorly represents what might reasonably be considered as the 'conventional alternative' if GM HT technology was not available.

The reasons why the conventional cropping data set is likely to be biased and unrepresentative of the levels of herbicide use that might reasonably be expected in the absence of biotechnology include:

- Whilst the degree of weed problems/damage vary by year, region and within region, farmers who continue to farm conventionally may be those with relatively low levels of weed problems, and hence see little, if any, economic benefit from using the GM HT traits targeted at minimal weed problems. Their herbicide usage levels therefore tend to be below the levels that would reasonably be expected on an average farm with more typical weed infestations;
- Some of the farms continuing to use conventional seed generally use extensive, low intensity production methods (including organic) which feature limited (below average) use of herbicides. The usage patterns of this sub-set of growers is therefore likely to understate usage for the majority of farmers if they all returned to farming without the use of GM HT technology;
- Some of the farmers using GM HT traits have experienced improvements in weed control from using this technology relative to the conventional control methods previously used. If these farmers were to now revert to using conventional techniques, it is likely that most would wish to maintain the levels of weed control delivered with use of the GM HT traits and therefore some would use higher levels of herbicide than they did in the pre GM HT crop days.

In addition, the use of no/low tillage production systems also tends to be less prominent amongst conventional soybean growers compared to GM HT growers. As such, the average herbicide ai/ha and EIQ/ha values recorded for all remaining conventional soybean growers tends to fall and be lower than the average would have been had all growers still been using conventional technology.

This problem of bias has been addressed, firstly by using the average recorded values for herbicide usage on conventional crops for years only when the conventional crop accounted for more than 50% of the total crop and, secondly, in other years (eg, from 1999 for soybeans, from 2001 for cotton and from 2007 for corn in the US) applying estimates of the likely usage if the whole US crop was no longer using crop biotechnology, based on opinion from extension and

industry advisors across the US⁶⁸. In addition, the usage levels identified from this methodology were cross checked (and subject to adjustment) against historic average usage levels of key herbicide active ingredients from the GfK dataset, so as to minimise the scope for understating or overstating likely usage levels on the conventional alternative.

Based on this approach, the respective values for conventional soybeans in the last nine years are shown in Table 40. These usage levels were then compared to typical and recommended weed control regimes for GM HT soybeans and recorded usage levels on the GM HT crop (which accounted for over 90% of the total crop since 2007), using the dataset from GfK. The key features of this comparison are that the average amount of active ingredient used on conventional soybeans, if this type of production were to replace the current area planted to GM HT soybeans, is roughly similar to current GM HT herbicide usage levels, but a switch to conventional soybeans would result in a higher average field EIQ/ha value (in other words the conventional soybean system would be worse for the environment in terms of toxicity than the GM HT system).

Table 40: Average ai use and field EIQs for conventional soybeans 2006-2015 to deliver equal efficacy to GM HT soybeans

Year	Ai use (kg/ha)	Field EIQ/ha
2006	1.49	36.2
2007	1.60	33.1
2008	1.62	36.2
2009	1.66	42.7
2010	1.71	46.1
2011	2.02	38.5
2012	2.14	44.0
2013	2.21	41.6
2014	2.19	42.2
2015	2.40	47.5

Sources: Sankala & Blumenthal (2006), Johnson & Strom (2008) and updated for this research for 2009-2015, including drawing on GfK usage data

Using this methodology for comparing conventional versus GM HT soybean herbicide usage, the estimated national level changes in herbicide use and the environmental impact associated with the adoption of GM HT soybeans⁶⁹ (Table 41) shows:

- In 2015, there was a small net decrease in herbicide ai use of 0.1% (0.07 million kg). The EIQ load was lower by a more significant 13% compared with the conventional (no/low tillage) alternative (ie, if all of the US soybean crop had been planted to conventional soybeans);

⁶⁸ Original analyses by Sankala and Blumenthal (2006) and Johnson and Strom (2008) were based on consultations with extension advisors in over 50 US states. Subsequent years have been updated by the author

⁶⁹ The approach compares the level of herbicide use (herbicide ai use and field EIQ/ha values) on the respective areas planted to conventional and GM HT soybeans in each year by comparing actual usage on the GM HT crop with the level of herbicide use that would reasonably be expected to be applied if this crop reverted to conventional production systems (non GM) and achieved the same level of weed control as delivered in the GM HT system

- Cumulatively since 1996, there have been savings in both active ingredient use and the associated environmental impact (as measured by the EIQ indicator) of -3.2% (32.7 million kg) in active ingredient usage and -23.3% for the field EIQ load.

Table 41: National level changes in herbicide ai use and field EIQ values for GM HT soybeans in the US 1996-2015

Year	ai decrease (kg)	EIQ saving (units)	% decrease in ai	% EIQ saving
1996	-19,425	2,670,982	-0.06	0.36
1997	-191,825	22,059,893	-0.47	2.28
1998	-588,830	68,422,098	-1.58	8.36
1999	3,278,025	252,080,123	7.37	22.91
2000	3,095,913	265,520,040	6.89	23.90
2001	3,326,588	315,804,125	7.44	28.54
2002	4,613,517	382,436,255	10.48	35.10
2003	2,573,857	370,120,593	5.82	33.77
2004	2,175,637	391,614,725	4.82	35.05
2005	2,418,454	386,415,219	5.62	36.26
2006	4,352,219	402,575,262	9.56	36.43
2007	2,812,022	224,258,717	6.83	26.31
2008	-277,900	279,284,006	-0.57	25.57
2009	408,283	450,049,449	0.78	34.12
2010	-1,884,457	504,119,014	-3.50	34.68
2011	3,640,381	200,566,762	6.00	17.35
2012	1,433,276	264,296,169	2.17	19.49
2013	1,142,180	147,055,676	1.68	11.53
2014	316,879	187,842,449	0.43	13.33
2015	75,405	206,831,365	0.09	13.14

b) Canada

The analysis of impact in Canada is based on comparisons of typical herbicide regimes used for GM HT and conventional soybeans and identification of the main herbicides that are no longer used since GM HT soybeans have been adopted⁷⁰. Details of these are presented in Appendix 3. Overall, this identifies:

- Up to 2006, an average ai/ha and field EIQ value/ha for GM HT soybeans of 0.9 kg/ha and 13.8/ha respectively, compared to conventional soybeans with 1.43 kg/ha of ai and a field EIQ/ha of 34.2;
- Post 2006, the same values for conventional with 1.32 kg/ai and a field EIQ/ha of 20.88 for GM HT soybeans.

Based on these values, at the national level⁷¹, in 2015, there was a net decrease in the volume of active ingredient used of 6.6% (-205,000 kg) and a 33% decrease in associated environmental impact (as measured by the EIQ indicator: Table 42). Cumulatively since 1997, there has been a

⁷⁰ Sources: George Morris Center (2004) and the (periodically) updated Ontario Weed Control Guide

⁷¹ Savings calculated by comparing the ai use and EIQ load if all of the crop was planted to a conventional (non GM) crop relative to the ai and EIQ levels on the actual areas of GM and non GM crops in each year

7.7% saving in active ingredient use (2.8 million kg) and a 23.6% saving in field EIQ/ha indicator value.

Table 42: National level changes in herbicide ai use and field EIQ values for GM HT soybeans in Canada 1997-2015

Year	ai saving (kg)	EIQ saving (units)	% decrease in ai (- = increase)	% EIQ saving
1997	530	20,408	0.03	
1998	25,973	1,000,094	1.85	0.06
1999	106,424	4,097,926	7.41	2.98
2000	112,434	4,329,353	7.41	11.93
2001	169,955	6,544,233	11.12	17.90
2002	230,611	8,879,827	15.75	25.36
2003	276,740	10,656,037	18.53	29.83
2004	351,170	13,522,035	20.38	32.82
2005	373,968	14,399,885	22.24	35.80
2006	84,130	10,191,227	4.85	24.54
2007	75,860	9,167,500	4.49	22.71
2008	96,800	11,726,000	5.63	28.52
2009	103,374	12,521,832	5.23	26.49
2010	113,729	13,776,201	5.38	27.27
2011	97,749	11,840,550	4.38	22.2
2012	119,977	14,533,032	5.0	25.3
2013	133,634	16,187,269	5.0	25.3
2014	149,969	18,165,957	4.69	23.8
2015	204,778	24,805,156	6.60	33.2

c) Brazil

Drawing on herbicide usage data from AMIS Global and Kleffmann, plus information from industry and extension advisers, the annual average use of herbicide active ingredient per ha in the early years of GM HT adoption was estimated to be a difference of 0.22kg/ha (ie, GM HT soybeans used 0.22 kg/ha less of herbicide active ingredient) and resulted in a net saving of 15.62 field EIQ/ha units. More recent data on herbicide usage, however, suggests a change in herbicide regimes used in both systems, partly due to changes in herbicide availability, prices, increasing adoption of reduced/no tillage production practices (in both conventional and GM HT soybeans) and weed resistance issues. As a result, estimated values for the respective systems in 2015 (see Appendix 3) were:

- An average active ingredient use of 2.59 kg/ha for GM HT soybeans compared to 2.53 kg/ha for conventional soybeans;
- The average field EIQ/ha value for the two production systems were 40.63/ha for GM HT soybeans compared to 47.4/ha for conventional soybeans⁷².

Based on the above herbicide usage data, (Table 43):

⁷² Inclusive of herbicides (mostly glyphosate) used in no/low tillage production systems for burndown. Readers should note that this data is based on recorded usage of key actives for the two production systems and does not indicate if equal efficacy to the GM HT system is achieved in the conventional system

- In 2015, the total herbicide active ingredient use was 2.3% higher on GM HT crops than it would likely have been if the crop had been conventional. The EIQ/ha environmental load was 13.5% lower than if the crop had been conventional;
- Cumulatively since 1997, there has been a 3.2% increase in herbicide active ingredient use (33.7 million kg). However, there has been a 6.4% reduction in the environmental impact (871 million field EIQ/ha units).

Table 43: National level changes in herbicide ai use and field EIQ values for GM HT soybeans in Brazil 1997-2015

Year	ai saving (kg negative sign denotes increase in ai use)	EIQ saving (units)	% decrease in ai (- = increase)	% EIQ saving
1997	22,333	1,561,667	0.1	0.3
1998	111,667	7,808,333	0.3	1.4
1999	263,533	18,427,667	0.7	3.3
2000	290,333	20,301,667	0.7	3.4
2001	292,790	20,473,450	0.7	3.4
2002	389,145	27,211,105	0.8	3.8
2003	670,000	46,850,000	1.2	5.9
2004	1,116,667	78,083,333	1.7	8.4
2005	2,010,000	140,550,000	2.9	14.4
2006	2,546,000	178,030,000	4.0	19.8
2007	-5,701,493	-45,847,926	-8.8	-4.9
2008	-5,704,705	-45,028,156	-16.3	-7.6
2009	-6,642,000	-54,763,974	-17.3	-8.5
2010	-7,529,650	-62,082,740	-19.1	-9.3
2011	-4,722,073	67,340,860	-7.0	6.1
2012	-5,663,575	80,767,507	-7.6	6.6
2013	-1,716,122	188,138,287	-2.3	13.3
2014	-1,842,482	201,991,139	-2.3	13.3
2015	-1,932,275	211,835,154	-2.3	13.5

d) Argentina

In assessing the changes in herbicide use associated with the adoption of GM HT soybeans in Argentina, it is important to take into consideration the following contextual factors:

- Prior to the first adoption of GM HT soybeans in 1996, 5.9 million ha of soybeans were grown, mostly using conventional tillage systems. The average use of herbicides was limited (1.1 kg ai/ha with an average field EIQ/ha value of 21);
- In 2015, the area planted to soybeans was 19.3 million ha. Almost all of this (99%) was planted to varieties containing the GM HT trait, and 90% plus of this area used no/reduced tillage systems that rely more on herbicide-based weed control programmes than conventional tillage systems.

Since 1996, the use of herbicides in Argentine soybean production has increased, both in terms of the volume of herbicide ai used and the average field EIQ/ha loading. In 2015, the estimated average herbicide ai use was 3.59kg/ha and the average field EIQ was 55.46/ha⁷³. Given 99% of the total crop is GM HT; these values effectively represent the typical values of use and impact for GM HT soybeans in Argentina.

These changes should, however, be assessed within the context of the fundamental changes in tillage systems that have occurred over the 1996-2015 period (some of which may possibly have taken place in the absence of the GM HT technology⁷⁴). Also, the expansion in soybean plantings has included some areas that had previously been considered too weedy for profitable soybean cultivation. This means that comparing current herbicide use patterns with those of 20 years ago is not a reasonably representative comparison of the levels of herbicide use under a GM HT reduced/no tillage production system and a conventional reduced/no tillage soybean production system.

To make a representative comparison of usage of the GM HT crop, with what might reasonably be expected if all of the GM HT crop reverted to conventional soybean production, requires identification of typical herbicide treatment regimes for conventional soybeans that would deliver similar levels of weed control (in a no tillage production system) as achieved in the GM HT system. To do this, we identified a number of alternative conventional treatments (see Appendix 3). Based on these, the current GM HT largely no tillage production system, has a higher volume of herbicide ai use (3.59 kg/ha compared to 3.23 kg/ha) than its conventional no tillage alternative. However, in terms of associated environmental impact, as measured by the EIQ methodology, the GM HT system delivers a small 1% improvement (GM HT field EIQ of 48.24/ha compared to 48.75/ha for conventional no/low tillage soybeans).

At the national level these reductions in herbicide use⁷⁵ are equivalent to:

- In 2015, a 12.8% increase in the volume of herbicide ai used (7 million kg) but a net 0.8% reduction in the associated environmental impact, as measured by the EIQ indicator (7.4 million EIQ/ha units);
- Cumulatively since 1996, there has been a net increase in herbicide ai use of +1.2% (+11.3 million kg) but a lower (net environmental gain) field EIQ load of 8.6% lower (1.34 million field EIQ/ha units) than the level that might reasonably be expected if the total Argentine soybean area had been planted to conventional cultivars using a no/low tillage production system.

e) Paraguay

The analysis presented below for Paraguay is based on AMIS Global usage data for the soybean crop and estimates of conventional alternative equivalents. Based on this, the respective differences for herbicide ai use and field EIQ values for GM HT and conventional soybeans in 2015 were:

⁷³ Source: AMIS Global (national herbicide usage data based on farm surveys)

⁷⁴ It is likely that the trend to increased use of reduced and no till systems would have continued in the absence of GM HT technology. However, the availability of this technology has probably played a major role in facilitating and maintaining reduced and no till systems at levels that would otherwise have not arisen

⁷⁵ Based on comparing the current GM HT no till usage with what would reasonably be expected if the same area and tillage system was planted to a conventional (non GM) crop and a similar level of weed control was achieved

- Conventional soybeans: average volume of herbicide used 3.3 kg/ha and a field EIQ/ha value of 51.84/ha;
- GM HT soybeans: average volume of herbicide used 3.57 kg/ha and a field EIQ/ha value of 44.43/ha.

Using these values, the level of herbicide ai use and the total EIQ load in 2015 were respectively 8.4% higher in terms of active ingredient use (+0.87 million kg), and lower by 13% in terms of associated environmental impact as measured by the EIQ indicator (24 million EIQ/ha units). Cumulatively, since 1999, herbicide ai use has been 5.9% higher (4.2 million kg⁷⁶) whilst the associated environmental impact, as measured by the EIQ indicator, was 6.1% lower (ie, despite an increase in active ingredient use, there was a net improvement in environmental impact associated with herbicide use).

f) *Uruguay*

Analysis for Uruguay also draws on AMIS Global data and estimates of the herbicide regime on conventional alternatives that would deliver a level of weed control with equal efficacy to GM HT soybeans. Based on this, the respective values for 2015 were:

- Conventional soybeans: average volume of herbicide used 2.82 kg/ha and a field EIQ/ha value of 48.75/ha;
- GM HT soybeans: average volume of herbicide used 2.98 kg/ha and a field EIQ/ha value of 47.48/ha.

Using these values, the level of herbicide ai use and the total EIQ load in 2015 were respectively 5.8% higher in terms of active ingredient use (+163,000 kg), but lower by 2.6% in terms of associated environmental impact as measured by the EIQ indicator (-1.3 million EIQ/ha units). Cumulatively, since 1999, herbicide ai use has been 3.2% higher (825,000 kg) whilst the associated environmental impact, as measured by the EIQ indicator, was 6.8% lower.

g) *Bolivia*

As no data on herbicide use in Bolivia has been identified, usage values and assumptions for differences in the adjacent country of Paraguay have been used. On this basis, the impact values are as follows:

- In 2015, a 7.2% increase in the volume of herbicide ai used (277,000 kg) but a net 11% reduction in the associated environmental impact, as measured by the EIQ indicator;
- Cumulatively since 2005, there has been a net increase in herbicide ai use of 6% (+1.3 million kg) but a net reduction in the field EIQ load of 4%.

h) *Romania*

Romania joined the EU at the beginning of 2007 and therefore was no longer officially permitted to grow GM HT soybeans. The analysis below therefore refers to the period 1999-2006. Based on herbicide usage data for the years 2000-2003 from Brookes (2005), the adoption of GM HT soybeans in Romania has resulted in a small net increase in the volume of herbicide active ingredient applied, but a net reduction in the EIQ load. More specifically:

⁷⁶ Up to 2006, estimated ai use was slightly higher for conventional relative to GM HT soybeans by 0.03 kg/ha

- The average volume of herbicide ai applied has increased by 0.09 kg/ha to 1.35 kg/ha;
- The average field EIQ/ha has decreased from 23/ha for conventional soybeans to 21/ha for GM HT soybeans.

This data has been used as the base for analysis of the environmental impact associated with herbicide use up to 2003. For the period 2003 to 2006, this has been updated by herbicide usage data from AMIS Global. Accordingly, in 2006, the average amount of herbicide active ingredient applied to the GM HT soybean crop was 0.87 kg/ha (field EIQ/ha of 13.03) compared to 0.99 kg/ha for conventional soybeans (field EIQ/ha of 19.09). Overall, during the 1999-2006 period, the total volume of herbicide ai use was 2% higher (equal to about 15,600 kg) than the level of use if the crop had been all non GM since 1999 but the field EIQ load had fallen by 11%.

With the banning of planting of GM HT soybeans in 2007, there has been a net negative environmental impact associated with herbicide use on the subsequent Romanian soybean crop, as farmers will have had to resort to conventional chemistry to control weeds. For example, based on AMIS Global herbicide usage data for 2011, when the entire crop was conventional, the average amount of herbicide active ingredient applied per ha had increased by 80% and the average field EIQ/ha rating by 95% relative to 2006 usage levels on GM HT soybeans. This suggests a significant deterioration in the environmental impact associated with herbicide usage on soybeans since the GM HT technology was banned from usage.

i) South Africa

GM HT soybeans have been grown in South Africa since 2000. Analysis of impact on herbicide use and the associated environmental impact of these crops (based on AMIS Global data and typical herbicide treatment regimes for GM HT soybeans and conventional soybeans: see Appendix 3) shows the following:

- Since 1999, the total volume of herbicide ai use has been 6.8% lower (equal to 484,000 kg of ai) than the level of use if the crop had been conventional;
- The field EIQ load has fallen by 21.5% (equal to 30 million field EIQ/ha units) since 1999 (in 2015 the EIQ load was 37% lower).

j) Mexico

Analysis of the impact on herbicide use and the associated environmental impact of the planting of GM HT soybeans in Mexico (planted on a farm level trial basis since 2004 on an annual area of between 10,000 ha and 20,000 ha) shows the following:

- Conventional soybeans: in 2015, the average volume of herbicide used was 1.76 kg/ha and the associated field EIQ/ha value was 41.02/ha;
- GM HT soybeans: the average volume of herbicide used was 1.62 kg/ha and the associated field EIQ/ha value was 24.83/ha in 2014.

Since 2004, the total volume of herbicide ai use has been 0.9% lower (equal to about 21,490 kg of ai) than the level of use if the crop had been conventional. The field EIQ load was also lower by 4.2%.

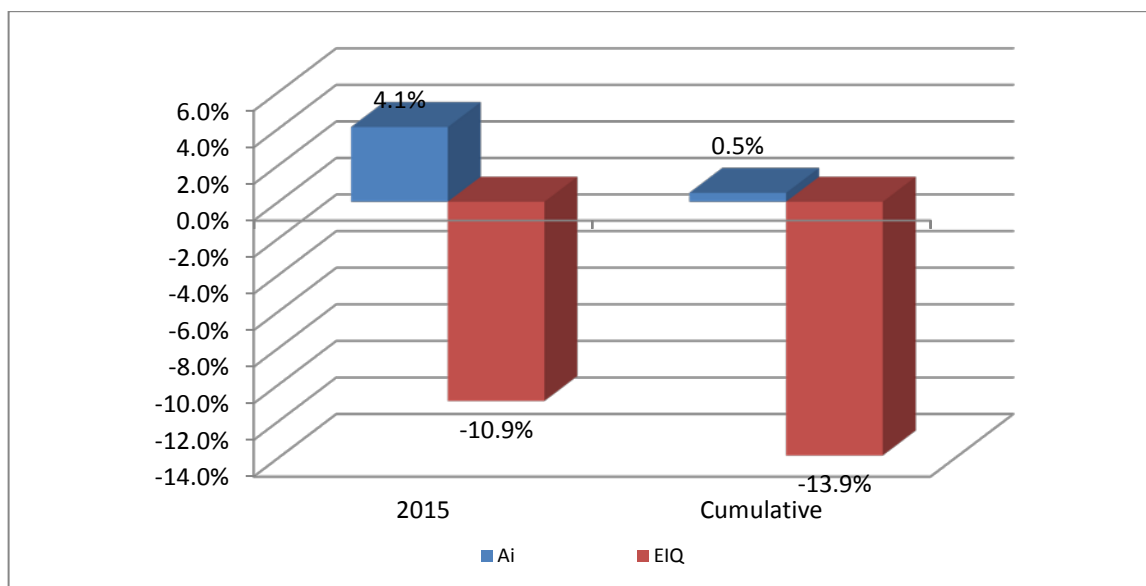
k) Summary of impact

Across all of the countries that have adopted GM HT soybeans since 1996, the net impact on herbicide use and the associated environmental impact⁷⁷ has been (Figure 15):

- In 2015, a 4.1% increase in the total volume of herbicide ai applied (9.8 million kg) but a 10.9% reduction in the environmental impact (measured in terms of the field EIQ/ha load);
- Since 1996, 0.5% more herbicide ai has been used (15.3 million kg) but the environmental impact applied to the soybean crop has fallen (an environmental improvement) by 13.9%.

This analysis takes into consideration changes in herbicide use, in recent years, on GM HT soybeans, that have occurred to specifically address the issue of weed resistance to glyphosate in some regions. Compared to several years ago, the amount of herbicide active ingredient applied and number of herbicides used with GM HT soybeans in many regions has increased, and the associated environmental profile, as measured by the EIQ indicator, deteriorated. However, relative to the conventional alternative, the environmental profile of GM HT soybean crop use has continued to offer important advantages⁷⁸ and in most cases, provides an improved environmental profile compared to the conventional alternative (as measured by the EIQ indicator).

Figure 15: Reduction in herbicide use and the environmental load from using GM HT soybeans in all adopting countries 1996-2015



⁷⁷ Relative to the expected herbicide usage if all of the GM HT area had been planted to conventional varieties, using the same tillage system (largely no/low till) and delivering an equal level of weed control to that obtained under the GM HT system

⁷⁸ 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

4.1.2 GM herbicide tolerant (to glyphosate) and insect resistant soybeans (Intacta)

GM IR soybeans (stacked with second generation a GM HT trait) were planted commercially in South America for the first time in 2013-14 (Brazil, Argentina, Uruguay and Paraguay). Drawing on pre-adoption insecticide usage data (source: AMIS Global) and post adoption site monitoring of conventional versus Intacta soybean plots (source: Monsanto), the following key points relating to insecticide use change have been identified:

- Intacta soybeans have enabled soybean growers to reduce the average number of insecticide treatments by about 4 (from an average of 8-10 sprays on conventional or GM HT only crops) in Brazil. In the other three adopting countries, average insecticide treatments have fallen by an average of 1.5;
- The average insecticide use saving from using Intacta soybeans has been about 0.17 kg of active ingredient and an associated field EIQ/ha saving of 17.25/ha in Brazil. In the other countries, the average insecticide use saving has been about 0.08 kg of active ingredient and an associated field EIQ/ha saving of 1.26/ha;

Based on these savings, in 2015, the use of this technology resulted in a reduction of 2.1 million kg of insecticide active ingredient use, equal to 2.3% of total insecticide used on the soybean crops in the four countries. The EIQ saving in 2015 was equal to 7.5%. Over the three years, the total insecticide active ingredient usage saving has been 3.64 million kg (-1.4%) and the associated environmental impact, as measured by the EIQ indicator fell by 4.3%.

4.1.3 GM Herbicide tolerant (GM HT) maize

a) The US

Drawing on the two main statistical sources of pesticide usage data (USDA and GfK), Table 44 and Table 45 summarise the key features:

- The average herbicide ai/ha used on a GM HT maize crop has been about 0.6 to 0.7 kg/ha lower than the average usage on the residual conventional crop in the period to about 2007. Since then, the differential between the increasingly GM HT crop and small conventional crop has narrowed, so that by 2010, average levels of active ingredient use were broadly similar and since 2011, the average amount of herbicide active applied to the GM HT crop has been higher than the usage on the small conventional crop;
- The average field EIQ/ha used on a GM HT crop has been about 20/ha units lower than the conventional crop, although in the last ten years the difference has narrowed and are now similar;
- The recent increase in ai use and the associated field EIQ/ha for GM HT maize mainly reflects the increasing concern about herbicide resistance and the adoption of integrated (reactive and proactive) weed management practices designed to address the issue of weed resistance to glyphosate (see section 4.1.9 for more detailed discussion). There has been an increasing proportion of the GM HT crop receiving additional treatments with herbicides such as acetochlor, atrazine, 2,4-D, mesotrione and S metolachlor as well as use of new chemistry such as tembutrione as recommended by public and private sector weed scientists.

Table 44: Herbicide usage on maize in the US 1996-2015

Year	Average ai use (kg/ha): NASS data	Average ai use (kg/ha) index 1998=100: GfK data	Average field EIQ/ha: NASS data	Average field EIQ/ha: GfK data
1996	2.64	N/a	54.4	N/a
1997	2.30	N/a	48.2	N/a
1998	2.47	100	51.3	62.0
1999	2.19	88.1	45.6	54.7
2000	2.15	87.8	46.2	54.5
2001	2.30	86.6	48.8	53.8
2002	2.06	82.4	43.4	51.1
2003	2.29	83.2	47.5	51.2
2004	N/a	80.0	N/a	48.9
2005	2.1	80.6	51.1	48.7
2006	N/a	79.5	N/a	47.7
2007	N/a	85.0	N/a	49.8
2008	N/a	88.7	N/a	50.9
2009	N/a	86.9	N/a	49.7
2010	2.36	90.5	49.2	51.4
2011	N/a	91.6	N/a	51.8
2012	N/a	95.6	N/a	53.8
2013	N/a	101.3	N/a	56.8
2014	2.45	100.7	47.0	56.2
2015	N/a	101.6	N/a	57.2

Sources and notes: derived from NASS pesticide usage data 1996-2003 and 2010 (no data collected in 2004, 2006-2009, 2011-2013, 2015), GfK data from 1998-2015. N/a = not available. Average ai/ha figures derived from GfK dataset are not permitted by GfK to be published.

Table 45: Average US maize herbicide usage and environmental load 1997-2015: conventional and GM HT

Year	Average ai/ha (kg) index 1998=100: conventional	Average ai/ha index 1998=100 (kg): GMHT	Average field EIQ: conventional	Average field EIQ: GMHT
1997	92.3	98.9	59.5	36.8
1998	100	100	63.1	36.9
1999	88.0	99.5	55.9	36.8
2000	89.1	97.9	56.5	35.7
2001	87.9	105.9	56.0	38.3
2002	85.3	99.5	54.5	35.6
2003	87.4	100.0	55.6	34.8
2004	85.3	101.1	54.7	35.2
2005	87.9	109.1	56.2	38.5
2006	88.0	111.8	56.4	40.1
2007	92.9	127.8	59.4	45.9
2008	88.0	140.1	56.2	50.2
2009	87.9	136.4	56.1	49.0
2010	90.3	142.2	58.1	50.8
2011	86.0	144.9	54.7	51.4

2012	86.0	151.9	55.1	53.7
2013	84.3	161.0	53.7	57.3
2014	88.3	159.4	55.5	56.3
2015	88.3	161.5	55.6	57.4

Sources and notes: derived from GfK. 1997 based on the average of the years 1998-1999. Average ai/ha figures derived from GfK dataset are not permitted by GfK to be published

As the herbicide usage data for the relatively small conventional crop presented in Table 45 is likely to be biased and unrepresentative (see section 4.1.1), the alternative that would deliver a similar level of weed control to the level delivered in the GM HT system, based on recommended practices from extension advisors and industry analysts⁷⁹ since 2007⁸⁰ (see appendix 1 for details) is summarised in Table 46. These conventional crop herbicide usage levels were then compared to recorded usage levels on the GM HT crop (which accounted for a majority of the total crop since 2007), using the dataset from GfK.

Table 46: Average ai use and field EIQs for conventional maize 2007-2015 to deliver equal efficacy to GM HT maize

Year	Ai use (kg/ha)	Field EIQ/ha
2007 and 2008	3.48	77.15
2009	3.78	78.81
2010	3.88	81.46
2011	3.43	84.10
2012	3.43	84.10
2013	3.37	60.84
2014	3.40	67.28
2015	3.41	67.36

Sources: Sankala & Blumenthal (2006), Johnson & Strom (2008) and updated for this research for 2009-2014, including drawing on GfK data

Through this more representative usage data for conventional corn and comparison with GM HT corn, it is evident that the average herbicide active ingredient use for conventional corn is higher than GM HT corn. The associated environmental load, as measured by the EIQ indicator, for conventional corn is also significantly worse for conventional corn when compared to GM HT corn.

At the national level (Table 47), in 2015, there has been an annual saving in the volume of herbicide active ingredient use of 10.1% (11.3 million kg). The annual field EIQ load on the US maize crop has also fallen by 13.2% in 2015 (equal to 291 million field EIQ/ha units). The cumulative decrease in active ingredient use since 1997 has been 9.9% (204 million kg), and the cumulative reduction in the field EIQ load has been 13.7%.

⁷⁹ The original analyses by Sankala and Blumenthal (2006) and Johnson and Strom (2008) were based on consultations with extension advisors in over 50 US states. Subsequent years have been updated by the author

⁸⁰ The conventional share of total maize plantings has been below 50% since 2007

Table 47: National level changes in herbicide ai use and field EIQ values for GM HT maize in the US 1997-2015

Year	ai decrease (kg)	EIQ saving (units)	% decrease in ai	% EIQ saving
1997	108,290	2,701,300	0.1	0.1
1998	1,862,202	43,612,096	1.9	2.1
1999	1,131,872	28,046,894	1.4	1.6
2000	1,893,007	47,009,679	2.2	2.6
2001	1,593,072	43,307,050	2.0	2.5
2002	2,643,638	72,297,763	3.2	4.2
2003	3,578,625	99,247,200	4.3	5.6
2004	4,285,776	126,300,520	5.2	7.1
2005	5,076,926	152,393,842	5.8	8.2
2006	6,162,189	185,550,355	7.4	10.4
2007	21,470,045	616,328,159	16.3	21.1
2008	17,242,687	540,738,699	15.6	22.0
2009	26,940,136	653,791,105	22.1	25.8
2010	27,996,062	704,261,601	22.0	26.4
2011	17,630,870	799,755,854	15.0	27.7
2012	1,806,896	812,586,944	11.8	27.0
2013	10,856,499	105,247,722	9.1	4.9
2014	12,657,665	327,474,109	11.1	14.5
2015	11,270,306	290,758,614	10.1	13.2

b) Canada

The impact on herbicide use in the Canadian maize crop has been similar to the impact reported above in the US. Using industry sourced information⁸¹ about typical herbicide regimes for conventional and GM HT maize (see Appendix 3), the key impact findings are:

- The herbicide ai/ha load on a GM HT crop has been between 0.88 kg/ha (GM glyphosate tolerant) and 1.069 kg/ha (GM glufosinate tolerant) lower than the conventional maize equivalent crop (average herbicide ai use at 2.71 kg/ha);
- The field EIQ/ha values for GM glyphosate and GM glufosinate tolerant maize are respectively 36/ha and 39/ha compared to 61/ha for conventional maize;
- At the national level in 2015 (based on the plantings of the different production systems), the reductions in herbicide ai use and the total field EIQ load were respectively 31.6% (1.1 million kg) and 38% (30.8 million: Table 48);
- Cumulatively since 1997, total national herbicide ai use has fallen by 17.3% (10.2 million kg) and the total EIQ load has fallen by 20.6% (275 million field EIQ units).

Table 48: Change in herbicide use and environmental load from using GM HT maize in Canada 1999-2015

Year	Total ai saving (kg)	Total field EIQ reductions (in units per hectare)
1999	59,324	1,439,924
2000	121,985	2,991,494

⁸¹ Including the Weed Control Guide (2004 and updated) from the Departments' of Agriculture in Ontario, Manitoba and Saskatchewan

2001	177,902	4,461,172
2002	255,305	6,377,468
2003	209,556	5,334,283
2004	203,320	5,234,173
2005	467,088	11,963,706
2006	501,479	13,110,306
2007	697,961	18,379,776
2008	565,770	14,979,769
2009	776,103	20,837,313
2010	584,446	15,557,562
2011	998,008	27,307,021
2012	1,127,079	30,904,561
2013	1,260,672	34,570,157
2014	1,045,165	28,660,528
2015	1,123,359	30,804,764

c) South Africa

Drawing on herbicide usage data from AMIS Global and industry level sources that compare typical herbicide treatment regimes for conventional and GM HT maize in South Africa (see appendix 3), the impact of using GM HT technology in the South African maize crop has been:

- On a per hectare basis in 2015 there has been a 0.3kg decrease in the amount of herbicide active ingredient used and an improvement in the average field EIQ of 12.46/ha;
- In 2015, at the national level, the amount of herbicide used was 494,000 kgs (-5.9%) lower than the amount that would probably have been used if the crop had all been planted to conventional seed. The total field EIQ load was 11.7% lower;
- Cumulatively since 2003, total national herbicide ai use has fallen by 2.5% (2.66 million kg) and the total EIQ load has fallen by 6.8%.

d) Argentina

Using a combination of AMIS Global herbicide usage data and industry estimates of typical herbicide regimes for the two different systems (see Appendix 3), the impact of GM HT maize use in Argentina has been as follows (first used commercially in 2004):

- The average volume of herbicide ai applied to GM HT maize was typically lower than the amount used on the conventional crop, although more recently the amount used on the GM HT crop has increased – in 2015 the average amount used on the GM HT crop was higher, at about 3.99 kg ai/ha compared to about 3.53 kg ai/ha for conventional maize;
- The average field EIQ/ha load for GM HT maize has been significantly lower than the conventional counterpart, although with the increase in ai use on the GM HT crop in recent years the difference between the two systems has narrowed. In 2015, the respective average EIQ/ha values were 71.8/ha for GM HT maize and 73.61/ha for conventional maize;
- The increase in the volume of herbicide used in 2015 was 1.04 million kg (+8.4%). Since 2004, there has, however been a net reduction in usage of 0.6% (-0.9 million kg);
- In terms of the field EIQ load, the reduction in 2015 was 2% (-4 million field/ha units) and over the period 2004-2015, the EIQ load factor fell by 6.7%.

e) Brazil

Brazil first used GM HT maize commercially in 2010, and in 2015, the area planted to seed containing this trait was 9.9 million ha. Drawing on a combination of sources (AMIS Global, industry and Galvao (2012-2015)); the estimated environmental impact associated with changes in herbicide use on this crop is as follows:

- The average amount of herbicide active use and associated field EIQ/ha rating for GM HT maize in 2015 was 3.91kg/ha and 70.29/ha respectively. This compared with conventional maize with herbicide active ingredient use of 3.99 kg/ha and a field EIQ rating of 86.15/ha;
- In 2015, the use of GM HT technology resulted in a saving in the use of 0.81 million kg of herbicide active ingredient (-1.3%) and a reduction in the EIQ rating of 11.6%;
- Cumulatively (2010-2015), the herbicide active ingredient usage saving has been 2.6% (-8.1 million kg), with an EIQ load reduction of 8.9%.

f) Uruguay

GM HT maize was first used in Uruguay in 2011, and in 2015 was planted on 86% of the total maize crop (71,380 ha of GM HT maize – all as stacked seed with both GM HT and GM IR traits). Industry contacts point to weed control practices and herbicides used in Uruguay to be very similar to those used in Argentina. We have therefore applied the Argentine herbicide usage assumptions for both conventional and GM HT maize crops in Uruguay. Based on these assumptions, since 2011, the adoption of GM HT maize has resulted in a net reduction in herbicide ai use on the maize crop of 19,800 kg of active ingredient (-0.2%) and a 9.3% improvement in the aggregate field EIQ/ha load.

g) Other countries

GM HT maize was also grown commercially in the Philippines, for the first time in 2006 and 702,000 ha used this technology in 2015. Weed control practices in maize in the Philippines are based on a combination of use of herbicides and hand weeding, with only about a third of the crop annually receiving herbicide treatments (ie, the majority of the crop, much of which is a subsistence crop, uses hand weeding as the primary form of weed control). The authors are not aware of any analysis which has examined the impact on herbicide use and the associated environmental 'footprint' of using GM HT maize in the Philippines.

GM HT maize was also grown in Colombia on 73,000 ha in 2015 and in Paraguay (2015, 252,000 ha). Analysis of the environmental impact associated with changes in herbicide use on these crops has not been possible due to a lack of data.

h) Summary of impact

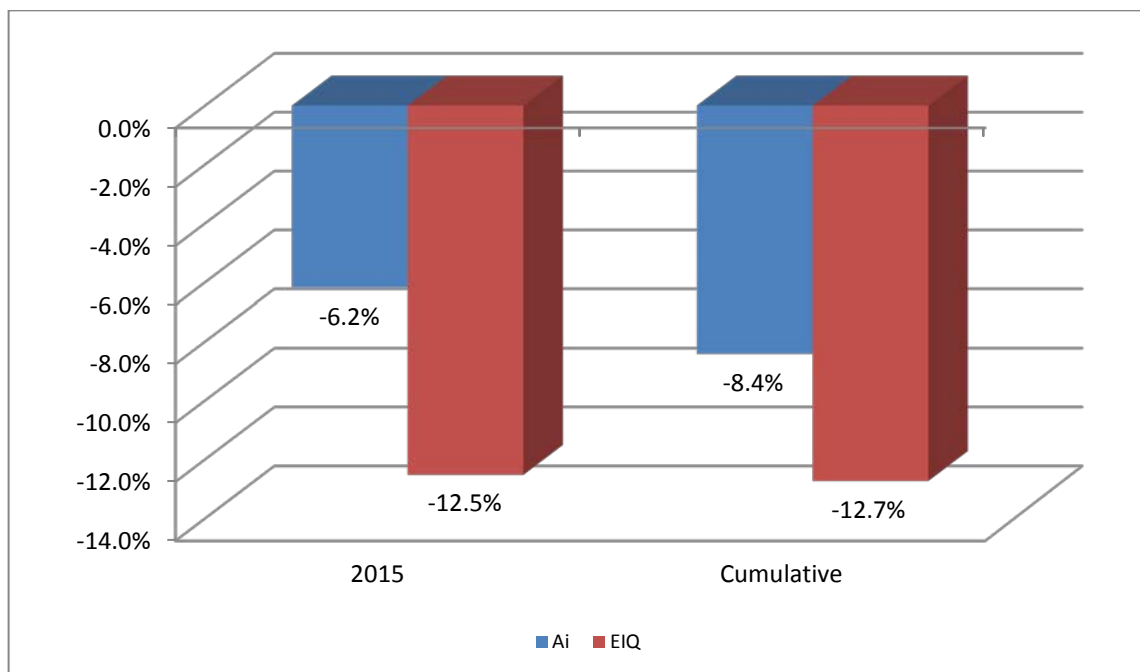
In the countries where GM HT maize has been most widely adopted, there has been a net decrease in both the volume of herbicides applied to maize and a net reduction in the environmental impact applied to the crop (Figure 16). More specifically:

- In 2015, total herbicide ai use was 6.2% lower (12.6 million kg) than the level of use if the total crop had been planted to conventional varieties. The EIQ load was also lower by 12.5%;

- Cumulatively since 1997, the volume of herbicide ai applied is 8.4% lower than its conventional equivalent (a saving of 226 million kg). The EIQ load has been reduced by 12.7%.

As with the GM HT soybean analysis, this analysis takes into consideration changes in herbicide use, in recent years, on GM HT maize that have specifically addressed the issue of weed resistance to glyphosate in some regions. The trend in herbicide use is broadly similar to soybeans, though less significant; the average amount of herbicide active ingredient use initially fell with the adoption of GM HT maize, but has, in the last few years, increased. At the same time, usage levels on conventional maize crops have also tended to increase, partly due to weed resistance (to herbicides other than glyphosate). Overall, however, the net environmental impact associated with the herbicides used on GM HT crops continues to represent an improvement relative to environmental impact associated with herbicide use on conventional forms of production.

Figure 16: Reduction in herbicide use and the environmental load from using GM HT maize in adopting countries 1997-2015



4.1.4 GM HT Herbicide tolerant (GM HT) cotton

a) The USA

Drawing on the herbicide usage data from the USDA and GfK, both the volume of ai used and the average field EIQ/ha on the US cotton crop remained fairly stable to the mid 2000s, although since then there has been a rise in usage (Table 49).

Table 49: Herbicide usage on cotton in the US 1996-2015

Year	Average ai use (kg/ha): NASS data	Average ai use (index 1998=100): GfK data	Average field EIQ/ha: NASS data	Average field EIQ/ha: based on GfK data
1996	1.98	N/a	53.19	N/a
1997	2.43	N/a	42.50	N/a
1998	2.14	100	35.60	45.3
1999	2.18	89.2	36.20	40.1
2000	2.18	95.4	35.20	42.5
2001	1.89	97.1	27.50	42.9
2002	N/a	96.9	N/a	42.3
2003	2.27	95.1	33.90	41.4
2004	N/a	103.1	N/a	44.5
2005	N/p	107.7	N/p	46.4
2006	N/a	105.0	N/a	45.8
2007	2.7	107.3	47.40	45.5
2008	N/a	113.2	N/a	48.8
2009	N/a	122.5	N/a	53.1
2010	2.5	142.0	53.11	61.5
2011	N/a	145.9	N/a	64.9
2012	N/a	159.2	N/a	69.4
2013	N/a	167.2	N/a	72.8
2014	N/a	178.9	N/a	72.9
2015	3.73	182.5	64.40	77.7

Sources and notes: derived from NASS pesticide usage data 1996-2003 and 2010 (no data collected in 2002, 2004, 2006, 2008, 2009, 2011-2014), GfK data from 1998-2015. N/p = Not presented - 2005 results based on NASS data are significantly different and inconsistent with previous trends and GfK data. These results have therefore not been presented. N/a = not available, Average ai/ha figures derived from GfK dataset are not permitted by GfK to be published

A comparison of average active ingredient usage for GM HT and conventional cotton (Table 50), shows that the average level of herbicide ai use (per ha) on GM HT cotton has been consistently higher than the average level of usage on the relatively small conventional cotton crop. In terms of the average field EIQ/ha, there has been a marginally lower average field EIQ rating for GM HT cotton in the first few years of adoption, but since then, the average field EIQ/ha rating has been lower for conventional cotton.

Table 50: Herbicide usage and its associated environmental load: GM HT and conventional cotton in the US 1997-2015

Year	Average ai use (index 1998=100): conventional cotton	Average ai use (index 1998=100): GM HT cotton	Average field EIQ/ha: conventional cotton	Average field EIQ/ha: GM HT cotton
1997	92.3	95	40.3	45.7
1998	100	100	43.5	46.1
1999	83.3	90.0	37.1	40.8
2000	91.0	92.8	41.3	41.7
2001	85.7	99.5	38.1	44.8
2002	83.8	99.3	37.7	43.8

2003	75.2	100.2	33.1	44.4
2004	73.5	107.4	32.9	47.4
2005	72.9	111.1	33.5	48.9
2006	79.4	106.6	35.2	48.1
2007	78.3	107.4	33.7	47.3
2008	89.9	112.4	37.5	50.5
2009	78.2	123.6	35.4	55.5
2010	101.2	141.3	42.7	63.5
2011	81.1	144.0	37.4	66.6
2012	56.7	156.0	26.3	70.9
2013	61.9	167.1	24.7	76.3
2014	69.2	173.4	30.5	77.1
2015	123.7	175.4	53.7	80.7

Sources and notes: derived from GfK 1998-2015. 1997 based on the average of the years 1997-1999. Average ai/ha figures derived from GfK dataset are not permitted by GfK to be published

As the herbicide usage data for the conventional crop presented in Table 50 is likely to be biased and unrepresentative⁸², an alternative that would deliver a similar level of weed control to the level delivered in the GM HT system, based on recommended practices from extension advisors and industry analysts⁸³ since 2006 (see appendix 1 for details), is summarised in Table 51. These conventional crop herbicide usage levels were then compared to recorded usage levels on the GM HT crop since 2006, using the dataset from GfK.

Table 51: Average ai use and field EIQs for conventional cotton 2006-2015 to deliver equal efficacy to GM HT cotton

Year	ai use (kg/ha)	Field EIQ/ha
2006	2.61	49.3
2007	2.98	52.1
2008	3.26	60.1
2009	3.59	64.6
2010	4.07	73.6
2011	4.48	85.0
2012	4.54	88.9
2013	4.96	95.3
2014	4.71	90.2
2015	4.82	89.0

Sources: based on Sankala & Blumenthal (2006), Johnson & Strom (2008) and updated to reflect changes in weed resistance management practices

Using this more representative herbicide usage data for conventional cotton and comparing it to recorded GM HT usage, the average herbicide active ingredient use and the associated environmental load, as measured by the EIQ indicator, for conventional cotton is higher than GM HT cotton. Since the mid 2000s, the average amount of herbicide active ingredient used on GM HT cotton has increased through a combination of additional usage of glyphosate (about a 30%

⁸² This is particularly relevant to cotton because much of the conventional cotton crop still being grown is concentrated in regions which traditionally use extensive production systems (eg, Texas)

⁸³ The original analyses by Sankala and Blumenthal (2006) and Johnson and Strom (2008) were based on consultations with extension advisors in over 50 US states. Subsequent years have been updated by the author

increase in usage per hectare) in conjunction with increasing use of other herbicides. All of the GM HT crop area planted to seed tolerant to glyphosate received treatments of glyphosate and at least one of the next five most used herbicides (trifluralin, acetochlor, S metolachlor, fomesafen and pendimethalin). This compares with 2006, when only three-quarters of the glyphosate tolerant crop received at least one treatment from the next five most used herbicides (2 4-D, trifluralin, pyriithiobic, pendimethalin and diuron). In other words, a quarter of the glyphosate tolerant crop used only glyphosate for weed control in 2006 compared to none of the crop relying solely on glyphosate in 2015. This suggests that US cotton farmers are increasingly adopting current recommended practices for managing weed resistant to glyphosate (and other herbicides).

Using this basis for comparing herbicide regimes for conventional and GM HT cotton at the national level (Table 52), shows that the impact of using the GM HT technology in 2015 resulted in a 7.4% decrease in the amount of herbicide use (1.14 million kg) and an 8.3% decrease in the associated environmental impact, as measured by the EIQ indicator. Cumulatively since 1997, there have been savings in herbicide use of 5.9% for ai use (17.1 million kg) and an 8.1% reduction in the associated environmental impact, as measured by the EIQ indicator.

Table 52: National level changes in herbicide ai use and field EIQ values for GM HT cotton in the US 1997-2015

Year	ai decrease (kg: + sign denotes increase in usage)	EIQ saving (units)	% decrease in ai	% EIQ saving
1997	194,126	2,495,419	1.3	0.8
1998	268,015	5,958,204	1.8	2.2
1999	1,111,761	24,163,708	6.8	8.0
2000	1,065,210	24,918,211	6.3	7.9
2001	710,162	19,638,472	4.1	6.1
2002	706,310	21,946,131	4.5	7.5
2003	512,302	16,927,322	3.9	6.9
2004	+4,001	9,371,068	0.0	3.5
2005	+268,966	4,851,593	+1.8	1.8
2006	+314,796	5,772,441	+2.0	1.9
2007	831,195	14,440,090	6.4	6.4
2008	895,615	20,390,870	9.0	11.1
2009	1,182,270	23,255,407	9.2	10.1
2010	1,834,949	35,911,952	10.2	11.1
2011	2,385,045	51,569,404	13.9	15.8
2012	1,804,574	53,160,969	10.5	15.8
2013	1,892,844	47,920,451	12.5	16.4
2014	1,151,240	44,453,353	6.6	13.3
2015	1,147,737	23,644,719	7.4	8.3

b) *Australia*

Drawing on information from the University of New England study from 2003⁸⁴, analysis of the typical herbicide treatment regimes for GM HT and conventional cotton and more recent industry assessments of conventional versus the newer 'Roundup Ready Flex' cotton that is widely used in Australia (see Appendix 3) shows the following:

- The herbicide ai/ha load on the original first generation GM HT crop was about 0.11 kg/ha higher (at 2.87 kg/ha) than the conventional cotton equivalent crop (2.77 kg/ha). With the introduction of the Roundup Ready Flex cotton in 2006, the average amount of herbicide active ingredient applied to the GM HT crop has, however fallen to an average level lower than the conventional equivalent. In 2015, the average herbicide ai use/ha on the GM HT crop was about 5.26 kg/ha compared to 7.47 kg/ha on the conventional equivalent crop⁸⁵;
- The average field EIQ/ha value for the original GM HT cotton was 65/ha, compared to 69/ha for conventional cotton. Under the Roundup Ready Flex versus conventional equivalent, the environmental load difference in favour of the GM HT cotton increased. Thus in 2015, the average field EIQ/ha for GM HT cotton was 90/ha compared to 143/ha for the conventional cotton equivalent;
- Based on the above data, at the national level (Table 53), in 2015, herbicide ai use has been 46.3% lower than the level expected if the whole crop had been planted to conventional cotton cultivars. The total field EIQ load was 61% lower;
- Cumulatively since 2000, total national herbicide ai use fell by 15.5% (2.94 million kg) and the total EIQ load decreased by 20.9%.

Table 53: National level changes in herbicide ai use and field EIQ values for GM HT cotton in Australia 2000-2015

Year	ai decrease (kg: + sign denotes increase in usage)	EIQ saving (units)	% change in ai: (+ sign denotes increase in usage)	% EIQ saving
2000	+1,290	106,030	+0.1	0.4
2001	+8,051	661,743	+0.8	3.6
2002	+9,756	801,898	+1.5	6.5
2003	+9,028	742,052	+1.7	7.2
2004	+17,624	1,448,593	+2.0	9.0
2005	+24,235	1,991,945	+2.9	12.1
2006	48,910	471,405	7.4	4.5
2007	23,718	228,602	8.4	5.2
2008	57,591	555,084	9.0	5.5
2009	83,111	801,049	10.3	6.3
2010	242,096	2,333,389	10.6	6.5
2011	527,386	13,934,069	19.3	28.0
2012	387,840	10,247,123	19.3	27.9
2013	694,208	14,885,431	34.7	40.4
2014	349,750	7,499,441	34.6	40.3

⁸⁴ Doyle et al (2003)

⁸⁵ Based on advisor recommendation to deliver equal efficacy of weed control to 'Flex cotton' and inclusive of weed control in the pre-plant phase

2015	595,467	14,371,774	46.3	60.8
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Note: 2015 values revised and include consideration of full resistant weed management practices and pre-plant weed control

c) South Africa

Using industry level sources that compare typical herbicide treatment regimes for conventional and GM HT cotton in South Africa (see appendix 3), the impact of using GM HT technology in the South African cotton crop has been:

- In 2015, there has been an average 0.1 kg decrease in the amount of herbicide active ingredient used and a 13% decrease in the environmental impact, as measured by the EIQ indicator (-4.3 field EIQ/ha units);
- At the national level, the amount of herbicide used in 2015 was 92 kg (0.5%) lower than the amount that would probably have been used if the crop had all been planted to conventional seed. The total field EIQ load was, however, a more significant 13.4% lower;
- Cumulatively since 2001, total national herbicide ai use increased by 1% (5,100 kg), whilst the total EIQ load fell by 7.7%. This shows that although the amount of herbicide used on the cotton crop has increased since the availability and use of GM HT cotton, the associated environmental impact of herbicide use on the cotton crop has fallen.

d) Argentina

GM HT cotton has been grown commercially in Argentina since 2002, and in 2015, all of the 410,000 ha cotton crop used seed containing this trait.

Based on industry level information relating to typical herbicide treatment regimes for GM HT and conventional cotton (see appendix 3), the impact of using this technology on herbicide use and the associated environmental impact has been:

- In 2015, the national level reduction in the amount of herbicide applied to the cotton crop was 0.27 million kg (-22%) lower than would otherwise have occurred if the whole crop had been planted to conventional varieties. The associated EIQ load was 18% lower;
- Cumulatively, since 2002, the amount of herbicide active ingredient applied had fallen 28% (-5 million kg). The field EIQ rating associated with herbicide use on the Argentine cotton crop fell 31% over the same period.

e) Other countries

Cotton farmers in Mexico, Colombia, Brazil and Paraguay have also been using GM HT technology since 2005, 2006, 2009 and 2013 respectively. No analysis is presented for the impact of using this technology in these countries because of the limited availability of herbicide usage data.

f) Summary of impact

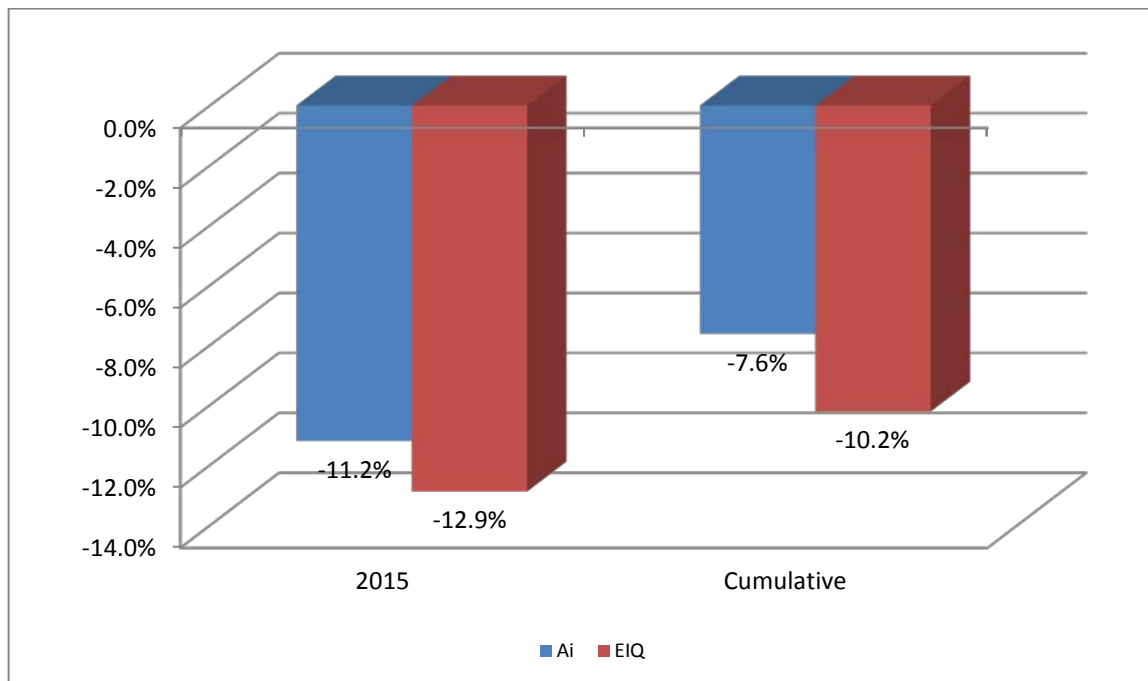
In 2015, the overall effect of using GM HT cotton technology (Figure 17) in the adopting countries has been a reduction in herbicide ai use⁸⁶ of 11.2% and a decrease in the total environmental

⁸⁶ Relative to the herbicide use expected if all of the GM HT area had been planted to conventional cultivars, using the same tillage system and providing the same level of weed control as delivered by the GM HT system

impact of 13%. Cumulatively since 1997, herbicide ai use fell by 7.6% (-25 million kg) and the associated environmental impact fell by 10.2%.

As with the analysis of herbicide use changes on GM HT soybeans and maize, this analysis takes into consideration changes in herbicide use, in recent years, on GM HT cotton that have occurred to specifically address the issue of weed resistance to glyphosate in some regions (notably the US). Such actions have resulted in a significant number of (US) cotton farmers using additional herbicides to glyphosate with GM HT cotton (that were not used in the early years of GM HT (to glyphosate) crop adoption) and can be seen in the increase in the average amounts of herbicide active ingredient applied per ha. Nevertheless, the net environmental impact associated with the herbicides used on GM HT crops in 2015 continues to represent an improvement relative to the environmental profile of herbicides that would likely be used if the crop reverted to using conventional (non-GM) technology.

Figure 17: Reduction in herbicide use and the environmental load from using GM HT cotton in the US, Australia, Argentina and South Africa 1997-2015



4.1.5 GM Herbicide tolerant (GM HT) canola

a) The US

Based on analysis of typical herbicide treatments for conventional, GM glyphosate tolerant and GM glufosinate tolerant canola identified in Sankala and Blumenthal (2003 & 2006), Johnson and Strom (2008), updates for 2014 undertaken as part of this research and data from the GfK dataset (see Appendix 3), the changes in herbicide use and resulting environmental impact arising from adoption of GM HT canola in the US since 1999⁸⁷ are summarised in Table 54. This shows consistent savings in terms of both the amount of herbicide active ingredient applied and the EIQ value for glyphosate and glufosinate tolerant canola relative to conventional canola.

⁸⁷ The USDA pesticide usage survey does not include coverage of canola

Table 54: Active ingredient and field EIQ differences conventional versus GM HT canola US 1999-2015

Year	ai saving GM HT (to glyphosate: kg/ha)	ai saving GM HT (to glufosinate: kg/ha)	EIQ saving GM HT (to glyphosate: field EIQ/ha)	EIQ saving GM HT (to glufosinate: field EIQ/ha)
1999	0.68	0.75	14.8	18.4
2000	0.68	0.75	14.8	18.4
2001	0.68	0.75	14.8	18.4
2002	0.57	0.75	17.7	18.4
2003	0.57	0.75	17.7	18.4
2004	0.79	0.83	21.2	19.8
2005	0.79	0.83	21.2	19.8
2006	0.7	0.78	19.8	18.8
2007	0.47	0.74	15.8	17.9
2008	0.47	0.74	15.8	17.9
2009	0.11	0.72	10.2	17.6
2010	0.09	0.57	9.9	14.6
2011	-0.02	0.65	8.2	16.1
2012	-0.11	0.65	6.5	16.6
2013 and 2014	-0.10	0.64	5.1	14.1
2015	-0.09	0.65	5.3	14.5

Sources: derived from Sankala & Blumenthal (2003 & 2006), Johnson & Strom (2008) and updates of this work, GfK

The reduction in the volume of herbicides used was equal to 186,000 kg of active ingredient (-25%) in 2015. In terms of the EIQ load, this had fallen by 6.4 million field EIQ units (-40%) compared to the load that would otherwise have been applied if the entire crop had been planted to conventional varieties. Cumulatively, since 1999, the amount of active ingredient use has fallen by 34%, and the EIQ load reduced by 46%.

b) Canada

Reductions in herbicide use and the environmental 'foot print' associated with the adoption of GM HT canola, have also been found in Canada:

- The analysis applied to the early years of adoption is based on the average volume of herbicide ai applied to GM HT canola being 0.65 kg/ha (GM glyphosate tolerant) and 0.39 kg/ha (GM glufosinate tolerant), compared to 1.13 kg/ha for conventional canola. This analysis has been applied to the years to 2004. From 2005, the conventional 'alternative' used includes the comparison of 'Clearfield' canola, which makes up the majority of the small area planted to non GM varieties⁸⁸. As in the US, in 2015, in terms of active ingredient use, GM HT canola tolerant to glyphosate uses about 0.09 kg/ha more and GM HT canola tolerant to glufosinate uses about 0.65 kg/ha less than the conventional alternative;
- The average field EIQ/ha load for GM HT canola has been consistently lower than the conventional counterpart (eg, in 2015, 17.59/ha for GM glyphosate tolerant canola, 8.4/ha for GM glufosinate tolerant canola and 22.89/ha for conventional canola);

⁸⁸ Herbicide tolerant by a non GM process, tolerant to the imidazolinone group of herbicides

- On the basis of these comparisons with conventional canola, the reduction in the volume of herbicide used was 2.62 million kg (a reduction of 30%) in 2015. Since 1996, the cumulative reduction in usage has been 20% (21.1 million kg);
- In terms of the field EIQ load, the reduction in 2015 was 43% (81 million field EIQ units) and over the period 1996-2015, the EIQ load factor fell by 32%.

c) Australia

Australia first allowed commercial planting of GM HT canola in 2008. Based on analysis of Fischer & Tozer (2009) which examined the use of GM HT (to glyphosate) canola relative to triazine tolerant (non GM) and 'Clearfield' canola, the average savings from adoption of the GM HT system were 0.4 kg/ha of active ingredient use and a reduction in the average field EIQ/ha of 2.74/ha (when weighted by type of conventional canola the GM HT replaced (ie, triazine tolerant or 'Clearfield')). These comparisons have been updated in recent years to reflect changes in weed management practices (notably for weed resistance management) and in 2015, the average⁸⁹ savings relative to conventional (HT) canola were 0.5 kg/ha for herbicide active ingredient usage and 22.31/ha for the field EIQ/ha value. At the national level, this resulted in a net saving of 0.23 million kgs of active ingredient (a 7.2% saving across the total canola crop) and a 6.5% reduction in the associated environmental impact of herbicide use (as measured by the EIQ indicator) on the 2015 Australian canola crop. Since 2008, the total herbicide active ingredient saving arising from use of GM HT canola has been about 0.79 million kg of active ingredient (-3.5%), with the EIQ load falling by 3%.

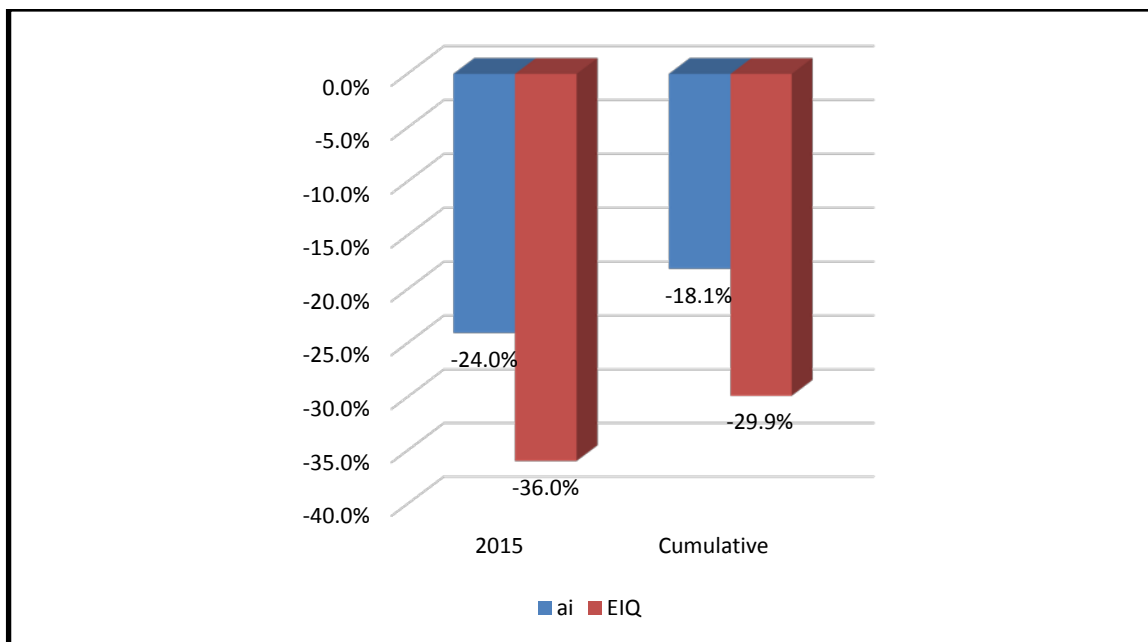
d) Summary of impact

In the countries where GM HT canola has been adopted, there has been a net decrease in both the volume of herbicides applied to canola and the environmental impact applied to the crop (Figure 18). More specifically:

- In 2015, total herbicide ai use was 24% lower (3 million kg) than the level of use if the total crop had been planted to conventional varieties. The EIQ load was also lower by 36%;
- Cumulatively since 1996, the volume of herbicide ai applied was 18% lower than its conventional equivalent (a saving of 25 million kg). The EIQ load had been reduced by 29.9%.

⁸⁹ Weighted by sales of seed between TT, 'Clearfield' and GM HT

Figure 18: Reduction in herbicide use and the environmental load from using GM HT canola in the US, Canada and Australia 1996-2015



4.1.6 GM HT sugar beet

The US

GM HT sugar beet was first planted on a small area in the US in 2007, and in 2015 accounted for 98% (454,270 ha) of the total US sugar beet crop. In terms of weed control, the use of this technology has resulted in a switch in use from a number of selective herbicides to glyphosate. Drawing on evidence from a combination of industry observers and the GfK dataset on pesticide use, the analysis below summarises the environmental impact (see appendix 3 for details of the typical conventional versus GM HT sugar beet treatment).

The switch to GM HT sugar beet has resulted in limited environmental impact associated with herbicide use changes. Sugar beet has traditionally been a crop in which several treatments of selective herbicides were used, often supplemented by manual weeding (due to the susceptibility of crop to damage from herbicides, especially at early stages of growth). The switch to using glyphosate tolerant crop technology resulted in the application of several herbicides (typically with low application rates in terms of amount of active ingredient applied) and manual weeding being replaced, initially by 2-3 applications of glyphosate. The net impact of this was broadly neutral or a limited reduction in the volume of herbicide use (in terms of active ingredient applied), coupled with a small net reduction (improvement) in the associated environmental impact, as measured by the EIQ indicator. In more recent years, the average amount of herbicide applied to the GM HT crop has tended to increase as farmers increasingly adopt more integrated weed management practices to address the development of weeds resistant to herbicides (both weeds resistant to glyphosate and other herbicides). Relative to the baseline profile of herbicide usage on conventional sugar beet, the impact of these changes has been a net increase in the average amount of herbicide applied to GM HT sugar beet crops and a marginal worsening of the environmental impact, as measured by the EIQ indicator. However, relative to the likely weed

control practices that would be required in 2015 to deliver the same level of weed control in a conventional crop as obtained in a GM HT crop, the comparison of herbicide regimes (see Appendix 3) suggests that the GM HT crop would use less herbicide, in terms of amount of active ingredient applied and would have a slightly lower EIQ/ha value than the conventional equivalent. Taking these changes into consideration, in 2015, the use of GM HT sugar beet resulted in a reduction in the amount of herbicide active ingredient used of about 28% (about +0.25 million kg) and a net reduction in the associated EIQ value of 8.8%. Cumulatively, since 2007, and taking into consideration the changes in herbicide usage and weed control practices that have occurred during this period relative to the conventional alternative⁹⁰, there has been a net increase in the amount of herbicide active ingredient used of 1.78 million kg (+24.9%) but a net reduction in the environmental load associated with herbicide use, as measured by the EIQ indicator of 0.9%.

GM HT sugar beet is also planted on a small area (about 15,000 ha in 2015) in Canada. Due to the lack of publicly available data on sugar beet herbicide use in Canada, no environmental impact analysis is presented. The impact is likely to be similar to the impact in the US.

4.1.7 GM IR maize

a) The US

Since 1996, when GM IR maize was first used commercially in the US, the average volume of insecticide use targeted at stalk boring and rootworm pests has fallen (Table 55). Whilst levels of insecticide use have fallen on both conventional and GM IR maize, usage by GM IR growers has consistently been lower than their conventional counterparts. A similar pattern has occurred in respect of the average field EIQ value. This data therefore suggests both that insecticide use *per se* has fallen on the US maize crops over the last nineteen years and that usage on GM IR crops has fallen by a greater amount. However, examining the impact of GM IR traits on insecticide use is more complex because:

- There are a number of pests for the maize crop. These vary in incidence and damage by region and year and typically affect only a proportion of the total crop. In the case of GM IR maize, this comprises two main traits that target stalk boring pests and the corn rootworm (second generation events have also included protection against cutworms and earworms). In the US, typically, a maximum of about 10% of the crop was treated with insecticides for stalk boring pests each year and about 30% of the US maize area treated with insecticides for corn rootworm. This means that assessing the impact of the GM IR technology requires disaggregation of insecticide usage specifically targeted at these pests and limiting the maximum impact area to the areas that would otherwise require insecticide treatment, rather than necessarily applying insecticide savings to the entire area planted to seed containing GM IR traits targeting these pests. This is particularly relevant if conclusions are to be drawn from examination of insecticide usage changes overall and of the proportion of the US maize crop typically receiving treatments of insecticides. Of note here has been the significant increase in the proportion of the US maize crop that has technically been in receipt of insecticides in terms of 'area treated' (equally applicable to GM IR and conventional crops) over the last 10 years. This reflects

⁹⁰ Which in effect is a largely hypothetical alternative given that almost all of the crop uses GM HT technology

- the growing preference by farmers for sowing maize seed that has been treated with the insecticides clothianidin and thiamethoxam and is unrelated to the adoption of GM IR technology;
- Typically, the first users of the GM IR technology will be those farmers who regularly experience economic levels of damage from the GM IR target pests. This means that once the level of adoption (in terms of areas planted to the GM IR traits) is in excess of the areas normally treated with insecticide sprays for these pests, it is likely that additional areas planted to the traits are largely for insurance purposes and no additional insecticide savings would arise (if assumed across all of the GM IR area). Secondly, comparing the level of insecticide use on the small conventional crop with insecticide use on the GM IR area would probably understate the insecticide savings, because the small conventional farmers tend to be those who do not suffer the pest problems that are the target of the GM IR technology and hence do not spray their crops with appropriate insecticide treatments;
 - The widespread adoption of GM IR maize technology has also resulted in 'area-wide' suppression of target pests such as stalk borers in maize crops. As a result, conventional farmers have benefited from this lower level of pest infestation and the associated reduced need to conduct insecticide treatments (see for example, Hutchison et al (2010)).

In order to address these issues, our approach has been to first identify the insecticides typically used to treat the stalk boring and rootworm pests and their usage rates from the GfK database and relevant literature (eg, Carpenter & Gianessi (1999)). These sources identified average usage of insecticides for the control of stalk boring pests and rootworm at 0.59 kg/ha (0.35 kg/ha from 2006⁹¹) and 0.4 kg/ha respectively. The corresponding field EIQ/ha values are 20/ha for stalk boring pests (10/ha from 2006) and 20.5/ha for rootworm.

These active ingredient and field EIQ savings were then applied to the maximum of the area historically receiving insecticide spray treatments for stalk boring pests and corn rootworm (10% and 30% respectively of the US maize crop) or the GM IR area targeting these pests, whichever was the smaller of the two areas. The maximum area to which these changes was applied in respect of rootworm insecticide savings was also reduced from 2011 in line with the increase in the area of the GM IR crop receiving applications of insecticides commonly used to target rootworm pests that reflect practices adopted by some farmers concerned that rootworm pests might be developing resistance to some of the GM IR traited seed (eg, in 2015, the maximum area on which the rootworm insecticide savings was 30% of the crop total less 0.62 million ha).

Based on this approach, at the national level, the use of GM IR maize has resulted in a saving in the volume of insecticide ai use of 77% (of the total usage of insecticides typically targeted at both corn boring pests and corn rootworm) in 2015 (4.8 million kg) and the annual field EIQ load fell by 82% in 2015 (equal to 221 million field EIQ/ha units). Since 1996, the cumulative decrease in insecticide ai use targeted at these pests has been 48% (65.9 million kg), and the cumulative reduction in the field EIQ load has been 51% (Table 56).

⁹¹ Reflecting changes in nature of insecticide use on conventional crops

Table 55: Average US maize insecticide usage and its environmental load 1996-2015: conventional versus GM IR (insecticides largely targeted at stalk boring and rootworm pests)

Year	Average ai/ha (kg): conventional	Average ai/ha (kg): GM IR	Average field EIQ: conventional	Average field EIQ: GM IR
1996	0.78	0.61	22.4	18.1
1997	0.76	0.59	22.0	17.7
1998	0.42	0.32	11.9	9.1
1999	0.40	0.39	12.1	11.5
2000	0.42	0.36	12.7	10.4
2001	0.31	0.31	10.0	9.6
2002	0.30	0.21	10.1	6.9
2003	0.29	0.20	9.0	5.7
2004	0.27	0.16	8.7	4.8
2005	0.20	0.17	6.5	5.1
2006	0.23	0.17	7.9	4.5
2007	0.20	0.14	8.3	3.8
2008	0.20	0.17	12.8	4.7
2009	0.17	0.15	12.1	4.5
2010	0.18	0.14	10.5	4.1
2011	0.14	0.11	10.2	3.2
2012	0.20	0.12	10.1	3.8
2013	0.15	0.12	6.1	3.8
2014	0.20	0.10	8.1	4.3
2015	0.20	0.12	8.0	5.0

Sources: derived from GfK (limited insecticides typically targeting control of stalk boring and rootworm pests and excluding seed treatments for which there is no significant difference in the pattern of usage between conventional and GM IR maize) and Carpenter & Gianessi (1999)

Table 56: National level changes in insecticide ai use and field EIQ values for GM IR maize in the US 1996-2015 (targeted at stalk boring and rootworm pests)

Year	ai decrease (kg)	EIQ saving (units)	% decrease in ai	% EIQ saving
1996	177,000	4,800,000	2.8	1.7
1997	1,443,310	39,140,608	22.5	13.6
1998	1,914,078	51,907,200	29.9	18.1
1999	1,847,762	50,108,800	28.8	17.4
2000	1,899,446	51,510,400	29.6	17.9
2001	1,807,524	49,017,600	28.2	17.0
2002	1,883,752	51,084,800	29.4	17.8
2003	2,005,348	57,484,618	31.3	20.0
2004	2,348,892	74,133,757	36.6	25.8
2005	2,653,718	88,882,618	41.0	30.9
2006	2,514,522	103,699,853	39.2	36.1
2007	4,987,715	225,553,601	77.8	78.4
2008	4,932,847	227,547,463	77.0	79.1
2009	4,992,493	230,298,867	77.9	80.1

2010	5,081,253	234,393,262	79.3	81.5
2011	5,324,824	245,628,976	83.1	85.4
2012	5,336,800	245,444,000	83.3	85.2
2013	5,126,178	234,555,349	79.9	81.5
2014	4,855,959	222,162,443	75.7	77.2
2015	4,817,014	220,933,267	76.6	82.2

Note: 2003 was the first year of commercial use of GM IR targeting corn rootworm

b) Canada

As in the US, the main impact has been associated with reduced use of insecticides. Based on analysis of a typical insecticide treatment regime targeted at corn boring pests prior to the introduction of GM IR technology that is now no longer required⁹², this has resulted in a farm level saving of 0.43 kg/ha of ai use and a reduction of the field EIQ/ha of 20.7/ha. Applying this saving to the area devoted to GM IR maize in 1997 and then to a maximum of 5% of the total Canadian maize area in any subsequent year, the cumulative reduction in insecticide ai use targeted at stalk boring pests has been 707,000 kg (-92%). In terms of environmental load, the total EIQ/ha load has fallen by 19.3 million units (-65%)⁹³.

c) Spain

Analysis for Spain draws on insecticide usage data from the early years of GM IR trait adoption, when the areas planted with this trait were fairly low (1999-2001 – from Brookes (2002)), and restricts the estimation of insecticide savings to a maximum of 10% of the total maize crop area which may have otherwise received insecticide treatments for corn boring pests. The difference in the data presented for Spain relative to the other countries is that the changes identified in insecticide usage relate to total insecticide use rather than insecticides typically used to target stalk boring pests. As a result of the adoption of GM IR maize, there has been a net decrease in both the volume of insecticide used and the field EIQ/ha load⁹⁴. More specifically:

- The volume of total maize insecticide ai use was 42% lower than the level would probably have been if the entire crop had been conventional in 2015 (-36,820 kg). Since 1998 the cumulative saving (relative to the level of use if all of the crop had been conventional) was 580,400 kg of insecticide ai (a 36% decrease);
- The field EIQ/ha load has fallen by 21% since 1999 (-15.6 million units). In 2015, the field EIQ load was 24% lower than its conventional equivalent.

d) Argentina

Although GM IR maize has been grown commercially in Argentina since 1998, the environmental impact of the technology has been very small. This is because insecticides have not traditionally been used on maize in Argentina (the average expenditure on all insecticides has only been \$1-\$2/ha), and very few farmers have used insecticides targeted at stalk boring pests. This absence of conventional treatments reflects several reasons including poor efficacy of the insecticides, the need to get spray timing right (at time of corn borer hatching, otherwise insecticides tend to be ineffective once the pest has bored into the stalk), seasonal and annual variations in pest pressure

⁹² And limiting the national impact to 5% of the total maize crop in Canada – the estimated maximum area that probably received insecticide treatments targeted at corn boring pests before the introduction of GM IR maize

⁹³ This relates to the total insecticide usage that would otherwise have probably been used on the Canadian maize crop to combat corn boring pests

⁹⁴ The average volume of all insecticide ai used is 0.96 kg/ha with an average field EIQ of 26/ha

and lack of awareness as to the full level of yield damage inflicted by the pest. As indicated in section 3, the main benefits from using the technology have been significantly higher levels of average yield, reduced production risk and improved quality of grain.

e) South Africa

Due to the limited availability of insecticide usage data in South Africa, the estimates of the impact of GM IR maize in South Africa presented below are based on the following assumptions:

- Irrigated crops are assumed to use two applications of cypermethrin to control stalk boring pests. This equates to about 0.168 kg/ha of active ingredient and a field EIQ of 6.11/ha (applicable to area of 200,000 ha);
- A dry land crop area of about 1,768,000 ha is assumed to receive an average of one application of cypermethrin. This amounts to 0.084 kg/ha of active ingredient and has a field EIQ of 3.06/ha;
- The first 200,000 ha to adopt GM IR technology is assumed to be irrigated crops.

Based on these assumptions:

- In 2015, the adoption of GM IR maize resulted in a net reduction in the volume of insecticides used of 165,300 kg (relative to the volume that would probably have been used if 1.768 million ha had been treated with insecticides targeted at stalk boring pests). The EIQ load (in respect of insecticide use targeted at these pests) was 100% lower than it would otherwise have been in the absence of use of the GM IR technology);
- Cumulatively since 2000, the reductions in the volume of ai use and the associated environmental load from sprayed insecticides were both 68% (1.8 million kg ai).

f) Brazil

The GM IR maize area in Brazil, in 2015, was 12.4 million ha (first planted commercially in 2008). Various stalk boring and other pests are commonplace in the Brazilian maize crop, with the Fall Armyworm (*Spodoptera*) being a major pest, and approximately 50% of the total annual crop has regularly been treated with insecticides targeting this pest (typically five spray treatments/crop).

The availability of GM IR maize that targets this pest has allowed users to decrease the number of insecticide spray runs from about five to two and significantly reduce the use of insecticides such as methomyl, lufenuron, triflumuron, spinosad and thiodicarb. As a result, the typical average saving in active ingredient use has been 0.356 kg/ha and the field EIQ/ha saving has been 21.5/ha⁹⁵. Applying these savings to the national level (constrained to a maximum of 48% of the total maize crop that has been the historic average annual area receiving insecticide treatments), this resulted in 2.69 million kg of insecticide active ingredient saving in 2015. This represents a 100% reduction in the environmental impact associated with insecticide use targeted at these pests. Cumulatively, over the eight years of use, the ai and field EIQ savings have been 89% lower than they would otherwise have been if this technology had not been used (a saving of 17.9 million kg of ai).

⁹⁵ Based on AMIS Global data for the 2006-2009 period

g) Colombia

The GM IR area in Colombia in 2015 was 68,620 ha (first grown in 2009). Based on analysis by Mendez et al (2011), this estimates that conventional maize growers (in the San Juan valley) typically use 0.56 kg/ai of insecticide to control maize pests, with an average field EIQ of 15.89/ha. Applying these savings to the GM IR area in 2009-2015, the technology has contributed to a saving in insecticide active ingredient use of 0.18 million kg. In terms of both active ingredient use and EIQ rating, this represents about a 66% reduction.

h) Other countries

GM IR maize has also been grown on significant areas in the Philippines (since 2003: 646,000 ha planted in 2015), in Uruguay (since 2004: 71,380 ha in 2015), in Honduras (since 2003: 27,000 ha in 2015) and in Paraguay (since 2013, 297,000 ha in 2015). Due to limited availability on insecticide use on maize crops⁹⁶, it has not been possible to analyse the impact of reduced insecticide use and the associated environmental impact in these countries.

i) Summary of impact

Across all of the countries that have adopted GM IR maize since 1996, the net impact on insecticide use and the associated environmental load (relative to what could have been expected if all maize plantings had been to conventional varieties) have been (Figure 19):

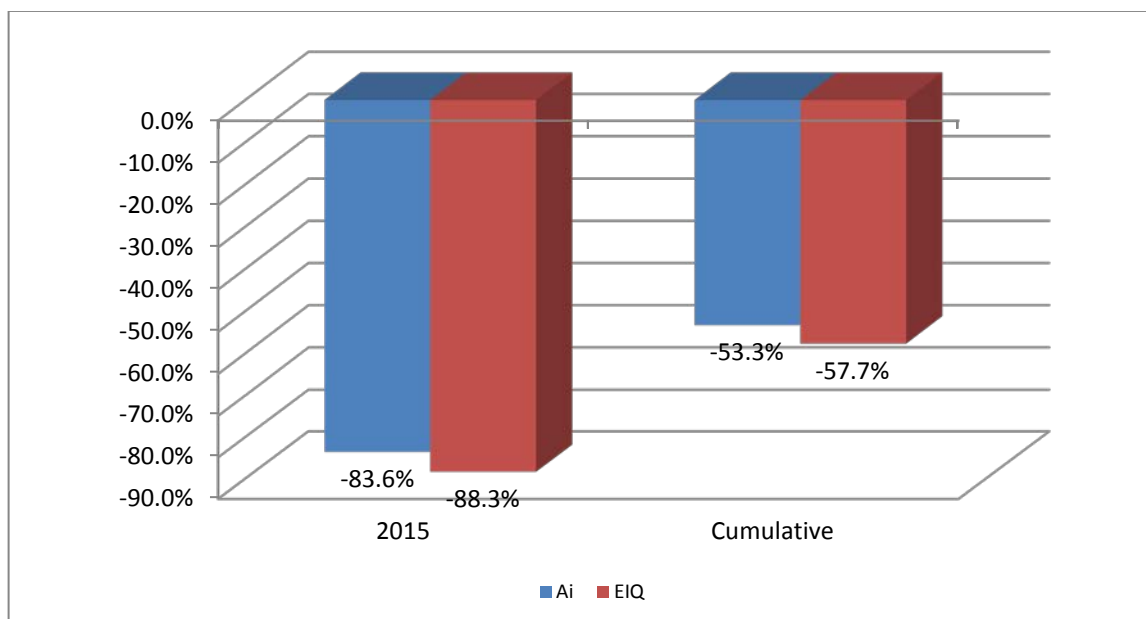
- In 2015, an 83.6% decrease in the total volume of insecticide ai applied (7.8 million kg) and an 88.3% reduction in the environmental impact (measured in terms of the field EIQ/ha load⁹⁷);
- Since 1996, 53.3% less insecticide ai has been used (87 million kg) and the environmental impact from insecticides applied to the maize crop has fallen by 57.7%.

⁹⁶ Coupled with the 'non' application of insecticide measures to control some pests by farmers in many countries and/or use of alternatives such as biological and cultural control measures

⁹⁷ Readers should note that these estimates relate to usage of insecticides targeted mainly at stalk boring and rootworm pests. Some of the active ingredients traditionally used to control these pests may still be used with GM IR maize for the control of some other pests that

at some of the GM IR technology does not target

Figure 19: Reduction in insecticide use and the environmental load from using GM IR maize in adopting countries 1996-2015



4.1.8 GM insect resistant (GM IR) cotton

a) The US

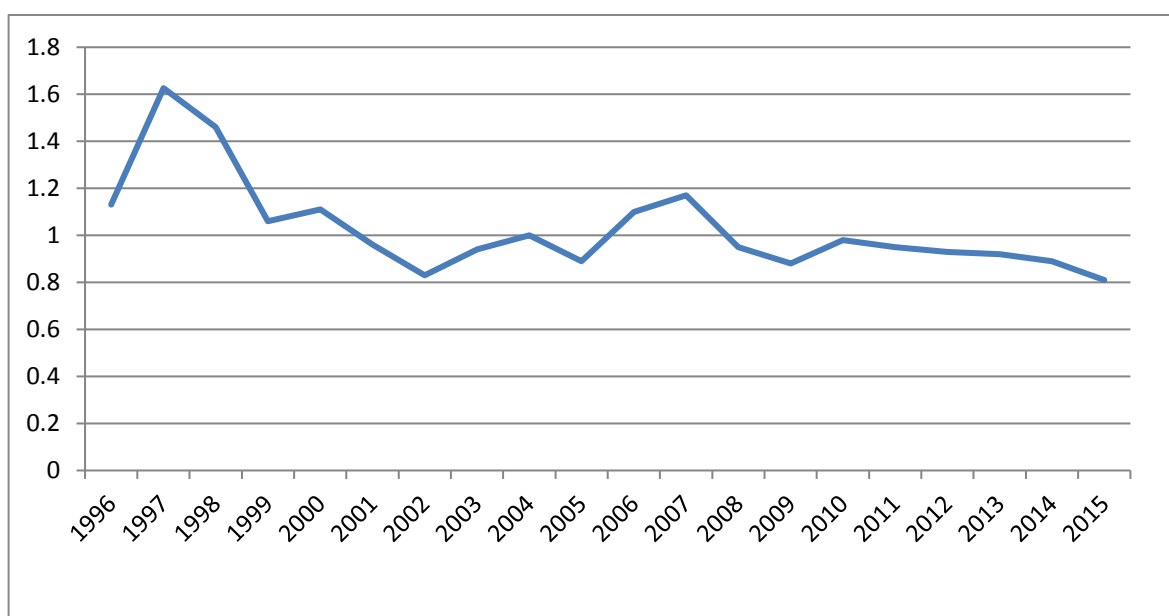
Whilst the annual average volume of insecticides used on the US cotton crop has fluctuated (as to be expected according to variations in regional and yearly pest pressures), there has been an underlying decrease in usage over the last 20 years (Figure 20). Applications on GM IR crops and the associated environmental impact have also been consistently lower for most years until 2007. Drawing conclusions from the usage data for the conventional versus GM IR cotton alone should, however, be treated with caution for a number of reasons (see also section 4.1.7):

- There are a number of pests for the cotton crop. These vary in incidence and damage by region and year and may affect only a proportion of the total crop. In the case of GM IR cotton, this comprises traits that target various *Heliothis* and *Helicoverpa* pests (eg, budworm and bollworm). These are major pests of cotton crops in all cotton growing regions of the world (including the US) and can devastate crops, causing substantial reductions in yield, unless crop protection practices are employed. In the US, all of the crop may typically be treated with insecticides for *Heliothis*/*Helicoverpa* pests each year although in some regions, notably Texas, the incidence and frequency of pest pressure tends to be much more limited than in other regions. In addition, there are pests such as boll weevil which are not targeted by current GM IR traits and crops receive insecticide treatments for these pests. This means that assessing the impact of the GM IR cotton technology requires disaggregation of insecticide usage specifically targeted at the *Heliothis*/*Helicoverpa* pests, and possibly limiting the maximum impact area to the areas that would otherwise require insecticide treatment, rather than necessarily applying insecticide savings to the entire area planted to seed containing GM IR traits targeting these pests;
- The widespread adoption of GM insect resistant technology has resulted in 'area-wide' suppression of target pests such as some *Heliothis*/*Helicoverpa* pests in cotton crops. As a

- result, some conventional farmers have benefited from this lower level of pest infestation and the associated reduced need to conduct insecticide treatments (Wu et al (2008));
- Typically, the first users of the GM IR technology will be those farmers who regularly experience economic levels of damage from the GM IR target pests. This means that once the levels of adoption (in terms of areas planted to the GM IR traits) become significant (above 50% of the US crop from 2005, and 84% in 2015), it is likely that the residual conventional crop tends to be found in regions where the pest pressure and damage from *Heliothis/Helicoverpa* pests is lower than would otherwise be the case in the regions where GM IR traits have been adopted. Hence, using data based on the average insecticide use on this residual conventional crop as an indicator of insecticide use savings relating to the adoption of GM IR traits probably understates the insecticide savings.

In order to address these issues, our approach has been to first identify the insecticides typically used to treat the *Heliothis/Helicoverpa* pests and their usage rates from the GfK database and relevant literature (eg, Carpenter & Gianessi (1999), Sankala & Blumenthal (2003 & 2006)). This identified average usage of a number of insecticides commonly used for the control of these pests in terms of amount of active ingredient applied, field EIQ/ha values and the proportion of the total crop receiving each active ingredient in a baseline period of 1996-2000. As most of these insecticide active ingredients are still in use in 2015 (for control of some other pests than those targeted by the GM IR trait), we have calculated the potential maximum usage of each insecticide for each year under the assumption no GM IR technology was used (using the baseline 1996-2000 adoption rates) and then compared these levels of use with actual recorded usage in each year. The difference between the two values represents the savings in insecticide usage attributed to the GM IR technology. Thus the annual savings estimated have been between 0.21 kg/ha and 0.85 kg/ha of active ingredient use and the field EIQ savings have been between 7.76/ha and 18/ha. In 2015, the savings were at the higher end of this range (0.94 kg/ai/ha and the field EIQ saving of 19.9/ha). These active ingredient and field EIQ savings were then applied to the GM IR area targeting these pests.

At the national level, the use of GM IR cotton has resulted in an annual saving in the volume of insecticide ai use of 63.5% in 2015 (2.5 million kg) and the annual field EIQ load on the US cotton crop also fell by 27.5% in 2015 (equal to 53 million field EIQ/ha units). Since 1996, the cumulative decrease in insecticide ai use has been 24.9% (19.5 million kg), and the cumulative reduction in the field EIQ load has been 19.6% (Table 57).

Figure 20: Average cotton insecticide usage: 1996-2015 (average kg active ingredient/ha)

Sources: derived from GfK and USDA NASS

Table 57: National level changes in insecticide ai use and field EIQ values for GM IR cotton in the US 1996-2015

Year	ai decrease (kg)	EIQ saving (units)	% decrease in ai	% EIQ saving
1996	213,371	7,708,736	3.1	3.9
1997	219,217	7,919,934	2.3	4.0
1998	236,617	8,548,572	3.2	4.3
1999	410,076	15,070,341	6.7	8.3
2000	564,221	19,685,752	10.2	11.2
2001	136,502	27,049,342	13.0	17.7
2002	511,015	18,226,708	13.5	14.6
2003	560,624	20,236,059	12.8	17.4
2004	649,509	23,980,157	17.4	15.5
2005	1,143,628	42,105,057	32.3	27.6
2006	1,193,080	43,623,825	18.4	27.6
2007	929,047	34,274,333	24.9	25.1
2008	613,891	22,331,832	27.2	22.5
2009	689,965	25,161,611	28.7	24.8
2010	1,187,626	43,639,636	32.6	28.2
2011	1,152,902	42,225,917	32.8	23.0
2012	1,185,258	43,862,290	39.8	23.7
2013	1,968,341	41,977,128	50.6	22.9
2014	2,795,226	59,567,486	59.1	29.7
2015	2,533,264	53,592,220	63.5	27.5

b) China

Since the adoption of GM IR cotton in China there have been substantial reductions in the use of insecticides. In terms of the average volume of insecticide ai applied to cotton, the application to a typical hectare of GM IR cotton in the earlier years of adoption was about 1.35 kg/ha, compared to 6.02 kg/ha for conventionally grown cotton (a 77% decrease)⁹⁸. In terms of an average field EIQ load/ha the GM IR cotton insecticide load was 61/ha compared to 292/ha for conventional cotton. More recent assessments of these comparisons (see Appendix 3 for 2015) put the average conventional treatment at 2.98 kg/ha, with a field EIQ/ha of 106.4/ha, compared to 1.75 kg/ha and a field EIQ/ha of 73.84/ha for GM IR cotton.

Based on these differences, the amount of insecticide ai used and its environmental load impact were respectively 41% and 30% lower in 2015 (Table 58) than the levels that would have occurred if only conventional cotton had been planted. Cumulatively since 1997, the volume of insecticide use has decreased by 30.7% (127.4 million kg ai) and the field EIQ load has fallen by 30.5% (5.9 billion field EIQ/ha units).

Table 58: National level changes in insecticide ai use and field EIQ values for GM IR cotton in China 1997-2015

Year	ai decrease (kg)	EIQ saving (units)	% decrease in ai	% EIQ saving
1997	158,780	7,843,630	0.6	0.6
1998	1,218,870	60,211,395	4.5	4.6
1999	3,054,180	150,874,530	13.6	13.9
2000	5,678,720	280,525,120	24.8	25.3
2001	10,152,580	501,530,930	35.0	35.7
2002	9,807,000	484,459,500	38.8	39.5
2003	13,076,000	645,946,000	42.5	42.5
2004	17,279,000	853,571,500	50.3	50.3
2005	15,411,000	761,293,500	50.2	50.2
2006	16,335,660	806,971,110	51.2	51.2
2007	3,382,000	158,236,180	20.5	19.8
2008	3,406,920	159,402,131	21.5	20.8
2009	3,177,300	148,658,727	22.8	22.0
2010	3,070,500	143,661,795	22.5	21.7
2011	3,499,925	163,753,620	23.1	23.9
2012	3,511,940	164,315,781	24.1	24.9
2013	5,766,600	149,307,312	33.9	24.9
2014	5,618,316	145,467,981	36.7	27.0
2015	3,779,520	97,791,360	40.9	29.6

Note: Change of basis in comparison data conventional versus GM IR cotton in 2007: see appendix 3 for current differences

⁹⁸ Sources: based on a combination of industry views and Pray et al (2001)

c) *Australia*

Using a combination of data from AMIS Global, industry sources and CSIRO⁹⁹, the following changes in insecticide use on Australian cotton have occurred:

- There has been a significant reduction in both the volume of insecticides used and the environmental impact associated with this spraying (Table 59);
- The average field EIQ/ha value of the Ingard technology was less than half the average field EIQ/ha for conventional cotton. In turn, this saving has been further increased with the availability and adoption of the Bollgard II cotton from 2003/04;
- The total amount of insecticide ai used and its environmental impact (Table 60) has been respectively 53% (0.3 million kg) and 58% lower in 2015 than the levels that would have occurred if only conventional cotton had been planted;
- Cumulatively, since 1996 the volume of insecticide use is 33.4% lower (18.3 million kg) than the amount that would have been used if GM IR technology had not been adopted and the field EIQ load has fallen by 34.5%.

Table 59: Comparison of insecticide ai use and field EIQ values for conventional, Ingard and Bollgard II cotton in Australia

	Conventional	Ingard	Bollgard II
Active ingredient use (kg/ha)	11.0 (2.1)	4.3	2.2 (0.91)
Field EIQ value/ha	220 (65)	97	39 (25.0)

Sources and notes: derived from industry sources and CSIRO 2005. Ingard cotton grown from 1996, Bollgard from 2003/04 (bracketed figures = values updated/revised from 2011)

Table 60: National level changes in insecticide ai use and field EIQ values for GM IR cotton in Australia 1996-2015

Year	ai decrease (kg)	EIQ saving (units)	%decrease in ai	% EIQ saving
1996	266,945	4,900,628	6.1	5.6
1997	390,175	7,162,905	9.1	8.4
1998	667,052	12,245,880	12.2	11.2
1999	896,795	16,463,550	15.2	14.0
2000	1,105,500	20,295,000	19.6	18.0
2001	909,538	16,697,496	23.8	21.9
2002	481,911	8,847,021	19.1	17.6
2003	427,621	7,850,352	20.1	18.4
2004	1,932,876	39,755,745	58.3	60.0
2005	2,177,393	44,785,011	64.4	66.2
2006	1,037,850	21,346,688	62.9	64.7
2007	486,886	10,014,368	69.2	71.1
2008	1,066,894	21,944,078	66.5	68.4
2009	1,403,591	28,869,319	69.9	71.9
2010	2,925,150	60,165,015	73.0	75.0

⁹⁹ The former making a direct comparison of insecticide use of Bollgard II versus conventional cotton and the latter a survey-based assessment of actual insecticide usage in the years 2002-03 and 2003-04

2011	656,285	22,076,545	53.9	58.6
2012	487,625	16,403,053	54.4	59.1
2013	474,309	15,955,117	53.7	58.3
2014	233,052	7,839,555	52.2	56.8
2015	301,452	10,140,440	53.1	57.8

d) *Argentina*

Adoption of GM IR cotton in Argentina has also resulted in important reductions in insecticide use¹⁰⁰:

- The average volume of insecticide ai used by GM IR cotton growers is 36.4% lower than the average of 0.736 kg/ha for conventional cotton growers in 2015;
- The average field EIQ/ha is also significantly lower for GM IR cotton growers (38.2/ha for conventional growers compared to 15.1/ha for GM IR growers);
- The total amount of ai used and its environmental impact (Table 61) have been respectively 41% (123,000 kg) and 55% lower (8.7 million field EIQ/ha units in 2015) than the levels that would have occurred if only conventional cotton had been planted;
- Cumulatively since 1998, the volume of insecticide use is 18.1% lower (1.27 million kg) and the EIQ/ha load 26% lower (86.3 million field EIQ/ha units) than the amount that would have been used if GM IR technology had not been adopted.

Table 61: National level changes in insecticide ai use and field EIQ values for GM IR cotton in Argentina 1998-2015

Year	ai decrease (kg)	EIQ saving (units)	% decrease in ai	% EIQ saving
1998	2,550	160,000	0.3	0.3
1999	6,120	384,000	0.8	1.1
2000	12,750	800,000	3.3	4.5
2001	5,100	320,000	1.1	1.6
2002	10,200	640,000	5.4	7.4
2003	23,664	1,484,800	17.6	23.9
2004	22,400	1,408,000	6.0	8.2
2005	9,180	576,000	3.2	4.4
2006	35,904	2,252,800	9.6	13.1
2007	66,218	4,154,880	21.8	29.7
2008	121,176	7,603,200	44.1	60.1
2009	145,370	9,121,280	35.9	48.9
2010	201,030	14,190,336	43.4	59.0
2011	165,158	11,658,250	42.3	57.6
2012	114,566	8,087,040	38.9	53.0
2013	157,978	11,151,360	36.4	49.5
2014	118,253	8,347,300	39.0	53.1
2015	123,118	8,690,688	40.8	55.5

Notes: derived from sources including CASAFE and AMIS Global. Decrease in impact for 2005 associated with a decrease in GM IR plantings in that year

¹⁰⁰ Based on data from Qaim and De Janvry (2005)

e) India

The analysis presented below is based on insecticide usage data from AMIS Global and typical spray regimes for GM IR and non GM IR cotton (source: Monsanto Industry, India 2006, 2009, 2011 and 2013). The respective differences for ai use (see appendix 3) and field EIQ values for GM IR and conventional cotton used in 2015 are:

- Conventional cotton: average volume of insecticide used was 1.77 kg/ha and a field EIQ/ha value of 74.83/ha;
- GM IR cotton: average volume of insecticide used was 0.68 kg/ha and a field EIQ/ha value of 18.85/ha.

Based on these values, the level of insecticide ai use and the total EIQ load in 2015 were respectively 58% (12.2 million kg) and 71% (633 million field EIQ/ha units) lower than would have been expected if the total crop had been conventional cotton. Cumulatively, since 2002, the insecticide ai use was 28.6% lower (99 million kg) and the total EIQ load 36.7% lower (4.85 billion EIQ/ha units).

f) Brazil

GM IR cotton was first planted commercially in 2006 (in 2015, on 477,000 ha, 50% of the total crop). Due to the limited availability of data, the analysis presented below is based on the experience in Argentina (see above). Thus, the respective differences for insecticide ai use and field EIQ values for GM IR and conventional cotton used as the basis for the analysis are:

- Conventional cotton: average volume of insecticide used is 0.736 kg/ha and a field EIQ/ha value of 38.2/ha;
- GM IR cotton: average volume of insecticide used 0.41 kg/ha and a field EIQ/ha value of 15.1/ha.

Using these values, the level of insecticide ai use and the total EIQ load in 2015 were respectively 24% (155,000 kg) and 30% (11 million EIQ/ha units) lower than would have been expected if the total crop had been conventional cotton. Cumulatively since 2006, the total active ingredient saving has been 0.98 million kg (12%) and the EIQ/ha load factor has fallen by 16%.

g) Mexico

GM IR cotton has been grown in Mexico since 1996, and in 2015, 118,000 ha (92% of the total crop) were planted to varieties containing GM IR traits.

Drawing on industry level data that compares typical insecticide treatments for GM IR and conventional cotton (see appendix 3), the main environmental impact associated with the use of GM IR technology in the cotton crop has been a significant reduction in the environmental impact associated with insecticide use on cotton. More specifically:

- On a per ha basis, GM IR cotton uses 31% less (-1.6 kg) insecticide than conventional cotton. The associated environmental impact, as measured by the EIQ indicator, of the GM IR cotton is a 32% improvement on conventional cotton (a field EIQ/ha value of 56.6/ha compared to 137/ha for conventional cotton);

- In 2015, at a national level, there had been a 28.6% saving in the amount of insecticide active ingredient use (191,000 kg) applied relative to usage if the whole crop had been planted to conventional varieties. The field EIQ load was 28% lower;
- Cumulatively since 1996, the amount of insecticide active ingredient applied was 13.4% (1.9 million kg) lower relative to usage if the Mexican cotton crop had been planted to only conventional varieties over this period. The field EIQ load was 13.2% lower than it would otherwise have been if the whole crop had been using conventional varieties.

h) Other countries

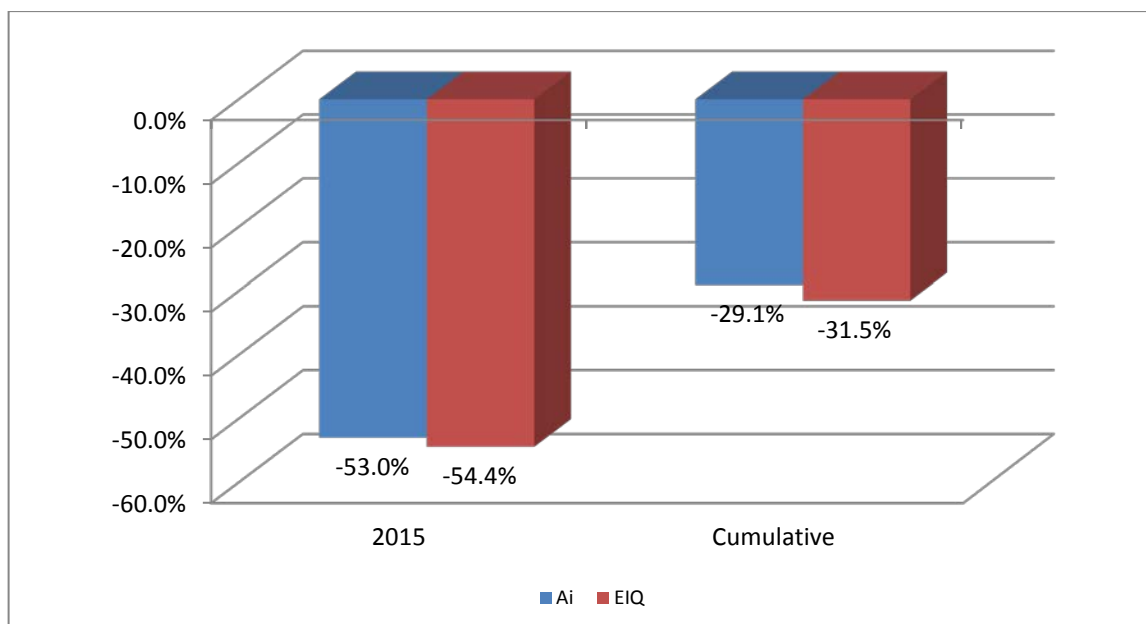
Cotton farmers in South Africa, Colombia, Burkina Faso, Pakistan, Myanmar and Sudan have also been using GM IR technology in recent years. Analysis of the impact on insecticide use and the associated environmental 'foot print' are not presented for these crops because of the lack of insecticide usage data.

i) Summary of impact

Since 1996, the net impact on insecticide use and the associated environmental 'foot print' (relative to what could have been expected if all cotton plantings had been to conventional varieties) in the main GM IR adopting countries has been (Figure 21):

- In 2015, a 53% decrease in the total volume of insecticide ai applied (19.3 million kg) and a 54% reduction in the environmental impact (measured in terms of the field EIQ/ha load);
- Since 1996, 29.1% less insecticide ai has been used (269 million kg) and the environmental impact from insecticides applied to the cotton crop has fallen by 31.5%.

Figure 21: Reduction in insecticide use and the environmental load from using GM IR cotton in adopting countries 1996-2015



4.1.9 Other environmental impacts - development of herbicide resistant weeds and weed shifts

As indicated in section 4.1.1, weed resistance to glyphosate has become a major issue affecting some farmers using GM HT (tolerant to glyphosate) crops.

This resistance development should, however, be placed in context. All weeds have the ability to develop resistance to all herbicides and there are hundreds of resistant weed species confirmed in the International Survey of Herbicide Resistant Weeds (www.weedscience.org), and reports of herbicide resistant weeds pre-date the use of GM HT crops by decades. There are, for example, 159 weed species that are resistant to ALS herbicides and 74 weed species resistant to photosystem II inhibitor herbicides. Worldwide there are currently (accessed March 2017) 37 weeds species resistant to glyphosate of which several are not associated with glyphosate tolerant crops (www.weedscience.org). In the US, there are currently 17 weeds recognised as exhibiting resistance to glyphosate, of which two are not associated with glyphosate tolerant crops. In Argentina, Brazil and Canada, where GM HT crops are widely grown, the number of weed species exhibiting resistance to glyphosate are respectively 9, 8 and 5. A few of the glyphosate-resistant species, such as marestail (*Conyza canadensis*), waterhemp (*Amaranthus tuberculatus*) and palmer pigweed (*Amaranthus palmeri*) in the US, are now reasonably widespread, with the affected area being possibly within a range of 40%-60% of the total area annually devoted to maize, cotton and soybeans.

Where farmers are faced with the existence of weeds resistant to glyphosate in GM HT crops, they are increasingly being advised to be more proactive and include other herbicides (with different and complementary modes of action) in combination with glyphosate and, in some cases, to revert to ploughing in integrated weed management systems. 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 control methods. At the macro level, these changes have already influenced the mix, total amount, cost and overall profile of herbicides applied to GM HT crops in the last 10 years.

For example, in the 2015 US GM HT soybean crop, 80% of the GM HT soybean crop received an additional herbicide treatment of one of the following (four most used, after glyphosate) active ingredients 2,4-D (used before crop planting), chlorimuron, fomesafen and sulfentrazone (each used primarily after crop planting). This compares with 14% of the GM HT soybean crop receiving a treatment of one of the next most used four herbicide active ingredients (after glyphosate) in 2006. As a result, the average amount of herbicide active ingredient applied to the GM HT soybean crop in the US (per hectare) increased by about 81% over this period. The increase in non-glyphosate herbicide use is primarily in response to public and private sector weed scientist recommendations to diversify weed management programmes and not to rely on a single herbicide mode of action for total weed management. It is interesting to note that in 2015, glyphosate accounted for a lower share of total active ingredient use on the GM HT crop (67%) as in 1998 when it accounted for 82% of total active ingredient use, highlighting that, although farmers are making additional use of non-glyphosate herbicides, they continue to realise value in using glyphosate because of its broad-spectrum activity. On the small conventional crop, the average amount of herbicide active ingredient applied increased by 84% over the same period reflecting a shift in herbicides used rather than increased dose rates for some herbicides. The increase in the use of herbicides on the conventional soybean crop in the US can also be partly

attributed to the on-going development of weed resistance to non-glyphosate herbicides commonly used and highlights that the development of weed resistance to herbicides is a problem faced by all farmers, regardless of production method. It is also interesting to note that since the mid-2000s, the average amount of herbicide active ingredient used on GM HT cotton in the US has increased through a combination of additional usage of glyphosate (about a 30% increase in usage per hectare) in conjunction with increasing use of other herbicides. All of the GM HT crop area planted to seed tolerant to glyphosate received treatments of glyphosate and at least one of the next five most used herbicides (trifluralin, acetochlor, S metolachlor, fomesafen and pendimethalin). This compares with 2006, when only three-quarters of the glyphosate tolerant crop received at least one treatment from the next five most used herbicides (2 4-D, trifluralin, pyriithiobic, pendimethalin and diuron). In other words, a quarter of the glyphosate tolerant crop used only glyphosate for weed control in 2006 compared to none of the crop relying solely on glyphosate in 2015. This suggests that US cotton farmers are increasingly adopting current/recent recommended practices for managing weed resistance (to glyphosate).

Relative to the conventional alternative, the environmental profile of GM HT crop use has, nevertheless, continued to offer important advantages and in most cases, provides an improved environmental profile compared to the conventional alternative (as measured by the EIQ indicator).

4.2 Carbon sequestration

This section assesses the contribution of GM crop adoption to reducing the level of greenhouse gas (GHG) emissions. The three main GHGs of relevance to agriculture are carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄). The scope for GM crops contributing to lowering levels of GHG comes from three principal sources:

- a) Reduced fuel use from fewer herbicide or insecticide applications;
- b) The use of 'no-till' (NT) and 'reduced-till' (RT) farming systems collectively referred to as conservation tillage, have increased significantly with the adoption of GM HT crops (see below for definitions). The GM HT technology has improved farmers' ability to control weeds, reducing the need to rely on soil cultivation and seed-bed preparation as means to getting good levels of weed control. The advantages of conservation tillage include:
 - Lower fuel costs (less ploughing);
 - Reduced labour requirements;
 - Enhanced soil quality and reduced levels of soil erosion, resulting in more carbon remaining in soil, which leads to lower GHG emissions¹⁰¹;
 - Improved levels of soil moisture conserving;
 - Reduced soil temperature fluctuations from the insulating properties of crop residues. This has a positive impact on both the physical, chemical and microbiological properties of soil (Mathew *et al* (2012)).

¹⁰¹ The International Panel on Climate Change (IPCC) has agreed that conservation/no till cultivation leads to higher levels of soil carbon. http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=174

- c) Additional carbon dioxide can be assimilated where the GM technology leads to higher yields and levels of production (see section 4.2.11).

Overall, the reduction of GHGs can be measured in terms of the amount of carbon dioxide removed from the atmosphere by reduced consumption of fuel and additional storing of carbon in the soil with no/reduced tillage practices.

In the analysis below, we have differentiated soil tillage systems into three categories depending upon their impact on soil disturbance:

- Conventional Tillage (CT): uses the traditional mouldboard plough followed by multiple tillage trips (up to 15) and results in less than 15% of old crop residue remaining on the surface;
- Reduced Tillage (RT): less intensive tillage resulting in reduced soil disturbance. RT includes 'mulch-till' that disturbs 100% of the soil and requires 1-3 tillage passes and 'ridge-till' where 4-6 inch high ridges are built during row cultivation and then 1-2 inches of the ridge are scraped off during planting. In RT 15%-30% of old crop residue remains on the surface after planting.
- No-till (NT): the least intensive form of tillage where a minimal amount of soil disturbance is made to ensure a good crop stand and yield. At least 30% of old crop residue commonly remains on the surface through which new crop seeds are planted.

4.2.1 Tractor fuel use

a) Reduced and no tillage

The adoption of conservation tillage systems, notably NT systems, have been facilitated by the availability of GM HT crops. To estimate fuel savings from reduced tillage, we have reviewed reports and data from a number of sources, of which the main ones were: the United States Department of Agriculture's (USDA) Energy Estimator for Tillage Model (2015), the Voluntary Reporting of Greenhouse Gases-Management Evaluation Tool (COMET-VR), Reeder (2010) and the University of Illinois (2006):

- The USDA's Energy Estimator for Tillage Model estimates diesel fuel use and costs in the production of key crops by specific locations across the USA and compares potential energy savings between conventional tillage (CT) and alternative tillage systems. The quantity of tractor fuel used for seed-bed preparation, herbicide spraying and planting in each of these systems is illustrated for soybeans planted in Illinois (Table 62). Conventional tillage requires 49.01 litres/ha, compared to mulch till at 40.88 litres/ha, ridge till 32.36 litres/ha and no-till 21.79 litres/ha;

Table 62: US soybean: tractor fuel consumption by tillage method (litres/ha) 2015

Year 1 – Illinois	Conventional tillage	Mulch till	Ridge-till	No-till
Chisel	0.00	9.35	0.00	0.00
Plough, mouldboard	17.48	0.00	0.00	0.00
Disk, tandem light finishing	3.74	3.74	0.00	0.00

Cultivator, field 6-12 in sweeps	6.92	6.92	0.00	0.00
Planter, double disk operation	4.12	4.12	4.12	0.00
Planter, double disk operation w/fluted coulter	0.00	0.00	0.00	5.04
Cultivator, row - 1st pass ridge till	0.00	0.00	5.79	0.00
Cultivator, row - 2nd pass ridge till	0.00	0.00	6.92	0.00
Sprayer, post emergence	1.22	1.22	0.00	1.22
Sprayer, insecticide post emergence	1.22	1.22	1.22	1.22
Harvest, killing crop 50% standing stubble	14.31	14.31	14.31	14.31
Total fuel use:	49.01	40.88	32.36	21.79
<i>Saving on conventional tillage:</i>		8.13	16.65	27.22

Source: USDA Energy Estimator 2015

- The fuel saving obtained by a switch from conventional tillage to mulch-till, ridge-till and no-till for corn and soybeans across the three most important crop management zones (CMZ's) in the US is illustrated in Table 63. The adoption of no-till in corn results in a 24.41 litre/ha saving compared with conventional tillage and in the case of soybeans, the no-till saving is 27.12 litre/ha¹⁰², a saving of 44.8% and 55.3% respectively;

Table 63: Total farm diesel fuel consumption estimate (litres/ha) 2015

Crop (crop management zones)	Conventional tillage	Mulch-till	Ridge-till	No-till
Corn (Minnesota, Iowa & Illinois)				
Total fuel use	54.50	46.98	36.39	30.09
Potential fuel savings over conventional tillage		7.52	18.11	24.41
Saving		13.8%	33.2%	44.8%
Soybeans (Iowa, Illinois & Nebraska)				
Total fuel use	49.01	38.62	33.74	21.89
Potential fuel savings over conventional tillage		10.39	15.27	27.12
Saving		21.2%	31.2%	55.3%

Source: USDA Energy Estimator 2015

- The Voluntary Reporting of Greenhouse Gases-Carbon Management Evaluation Tool (COMET-VR) gives a higher reduction of 41.81 litres/ha when conventional tillage is replaced by no-till on non-irrigated corn and a reduction of 59.68 litres/ha in the case of soybeans in Nebraska;
- The University of Illinois (2006) compared the relative fuel use across four different tillage systems for both corn and soybeans. The 'deep' tillage and 'typical' intensive systems required 36.01 litres/ha compared to the strip-till and no-till systems which used 22.92 litres/ha – a reduction of 13.09 litres/ha;
- Reeder (2010) estimated that RT or NT typically uses 19 to 38 litres/ha less diesel fuel than conventional tillage;

¹⁰² These figures have not differed since 2012 when the USDA Energy Estimator for Tillage Model (<https://ecat.sc.egov.usda.gov/>) was last updated

- Analysis by the Jasa (2002) at the University of Nebraska calculated fuel use based on farm survey data for various crops and tillage systems. Intensive tillage (resulting in 0%-15% crop residue) using the mouldboard plough uses 49.39 litres/ha, reduced tillage (15%-30% residue) based on a chisel plough and/or combination of disk passes uses 28.34-31.24 litres/ha, conservation tillage (>30% residue) based on ridge tillage 25.16 litre/ha and no-till and strip-tillage 13.38 litres/ha - a reduction of 36.01 litres/ha compared to intensive tillage;
- Other analysts have suggested similar savings in fuel from no-till. For example, the USDA 2007 Farm Bill Theme Paper 'Energy and Agriculture' stated: '*During the past couple of decades, the Natural Resources Conservation Service (NRCS) has helped farmers adopt no-till practices on about 25 million hectares of cropland. Assuming an average saving of 33.13 litres/ha in diesel fuel, this amounts to savings of 821 million litres of diesel fuel per year with cost savings to farmers of about \$500 million per year.*'

In our analysis¹⁰³ presented below, it is assumed that the adoption of NT farming systems in soybean production reduces cultivation and seedbed preparation fuel usage by 27.12 litres/ha compared with traditional conventional tillage and in the case of RT cultivation by 10.39 litres/ha. In the case of maize, NT results in a saving of 24.41 litres/ha and in the case of RT 7.52 litres/ha, compared with conventional intensive tillage. These are conservative estimates and are in line with the USDA Fuel Estimator for soybeans and maize. The amount of tractor fuel used for seed-bed preparation, herbicide spraying and planting in each of these systems is shown in Table 64.

Table 64: Tractor fuel consumption by tillage method (litre/ha) 2015

Tillage system	US soybean litres/ha	US maize litres/ha
Intensive tillage: traditional cultivation: mouldboard plough, disc and seed planting etc.	49.01	54.50
Mulch till - Reduced tillage (RT): chisel plough, disc and seed planting	38.62	46.98
No-till (NT): fertiliser knife, seed planting plus 2 sprays	21.89	30.09

Source: Adapted from USDA Fuel Estimator 2015

In terms of GHG, each litre of tractor diesel consumed contributes an estimated 2.67¹⁰⁴ kg of carbon dioxide into the atmosphere. The adoption of NT and RT systems in respect of fuel use therefore results in reductions of carbon dioxide emissions of 72.41 kg/CO₂/ha and 27.74 kg/CO₂/ha respectively for soybeans and 65.17 kg/CO₂/ha and 20.08 kg/CO₂/ha for maize.

b) Reduced application of herbicides and insecticides

For both herbicide and insecticide spray applications, the quantity of energy required to apply pesticides depends upon the application method. For example, in the US, a typical method of

¹⁰³ In previous editions of this report, the authors have used different savings that reflect changing estimates of fuel use by the USDA Energy Estimator. In reports covering the period up to 2010 savings of 27.22 litres/ha for NT and 9.56 litres/ha for RT compared to CT were used

¹⁰⁴ In previous editions of this report the authors have applied a co-efficient of 2.75 to convert 1 litre of diesel to kgs of carbon dioxide. This report (and the reports covering the period 1996-2011, 1996-2012, 1996-2013 and 1996-2014) uses the updated figure of 2.6676 rounded to 2.67.

application is with a 50-foot boom sprayer which consumes approximately 0.84 litres/ha¹⁰⁵ (Lazarus (2013)). One less spray application therefore reduces carbon dioxide emissions by 2.24 kg/ha¹⁰⁶. Approximately 20% of pesticides in the US are applied by crop dusters which have a marginally lower carbon footprint than boom sprayers (National Agricultural Aviation Association 2013).

The conversion of one hectare of conventional tillage to no-till equates to a saving of approximately 483 km travelled by a standard family car¹⁰⁷ and one less spray pass per hectare is equal to a saving of nearly 15 km travelled.

4.2.2 Soil carbon sequestration

The use of RT/NT farming systems increases the amount of organic soil carbon in the form of crop residue that is stored or sequestered in the soil and therefore reduces carbon dioxide emissions to the environment. Appendix 5 summarises some of the key research which has examined the relationship between carbon sequestration and different tillage systems. This literature review shows that the amount of carbon sequestered varies by soil type, cropping system, eco-region and tillage depth. It also shows that tillage systems can impact on levels of other GHG emissions such as methane and nitrous oxide and on crop yield.

Overall, the literature highlights the difficulty in estimating the contribution NT/RT systems can make to soil carbon sequestration, because of the dynamic nature of soils, climate, cropping types and patterns. If a specific crop area is in continuous NT crop rotation, the full soil carbon sequestration benefits described in the literature can be realised. However, if the NT crop area is returned to a conventional tillage system, a proportion of the soil organic carbon gain will be lost. The temporary nature of this form of carbon storage only becomes permanent when farmers adopt a continuous NT system, which, as indicated earlier, is highly dependent upon having effective herbicide-based weed control systems.

Complex models are available to estimate the level of carbon sequestered depending upon historic, present and future cropping systems. For example, the USDA's COMET-Planner applies emission reduction coefficients for changes in tillage practice from conventional tillage to NT and RT based on a meta-analysis of the literature on the subject (Table 65). In this tool coefficients are generalized at the national-scale and differentiated by dry and humid climate zones with the values shown being emission reductions relative to baseline management (positive values mean a decrease in emissions due to the implementation of the tillage practice). For example, the conversion of one hectare of crop land from CT to NT in a moist/humid environment will result in 1,037.8 kg of carbon dioxide/ha/year being sequestered; this is equivalent to 282.8 kg carbon/ha/year.

¹⁰⁵ In previous editions of this report (up to and including the 5th report covering 1996-2009) the authors have used 1.31 litres/ha.

¹⁰⁶ Given that many farmers apply insecticides via sprayers pulled by tractors, which tend to use higher levels of fuel than self-propelled boom sprayers, the estimates used in this section (for reductions in carbon emissions), which are based on self-propelled boom application, probably understate the carbon benefits.

¹⁰⁷ Assumed standard family car carbon dioxide emission rating = 150 grams/km. Therefore 72.41 kg of carbon dioxide divided by 150g/km = 483 km.

Table 65: COMET-Planner: carbon sequestration by conservation practice (average)

Conservation practice	Climate zone	Carbon dioxide (kg CO ₂ eq/ha/year)	Carbon (kg carbon/ha/year)
CT to NT	Dry/semi arid	568.3	154.9
	Moist/humid	1,037.8	282.8
CT to RT	Dry/semi arid	247.1	67.3
	Moist/humid	321.2	87.5

Notes:

- 1 kg carbon equals 3.67 kg carbon dioxide

Our analysis for the US uses the COMET-VR 2.0 tool¹⁰⁸ for three key soybean and corn production states and assumes the adoption of NT from CT in all states, a clay loam soil with average fertiliser usage, a non-irrigated corn-soybean rotation in Minnesota and Illinois and a soybean-corn-winter-wheat rotation in South Dakota. Using the COMET-VR 2.0 tool, the level of carbon sequestered estimated to be stored is higher with NT by 117.5, 114.4 and 112.9 kg carbon/ha/year respectively compared to the CT system for each of the three states for the projected period 2013-2023.

Analysis using the Michigan State University - US Cropland Greenhouse Gas Calculator¹⁰⁹ for corn-soybean rotations in the same locations over a ten year projected period estimated that NT sequesters an additional 123 kg carbon/ha/year compared to RT and 175 kg carbon/ha/year compared to CT.

Analysis of individual crops using the Michigan State University - US Cropland Greenhouse Gas indicates that NT corn is a net carbon sink of 244 kg carbon/ha/year whereas NT soybean is a marginal net source of carbon of 43 kg carbon/ha/year. The difference between corn NT and CT is 247 kg carbon/ha/year and for soybeans 103 kg carbon/ha/year (Table 66).

Table 66: Summary of the potential of corn and soybeans cultivation systems to reduce net emissions or sequester carbon (kg of carbon/ha/year)

		Carbon sequestered (kg/ha/year)	Carbon sequestered - difference to NT (kg/ha/year)
Corn	Conventional	-3	-247
	Reduced	72	-171
	No-till	244	0
Soybean	Conventional	-146	-103
	Reduced	-114	-72
	No-till	-43	0

Source: Michigan State University - US Cropland Greenhouse Gas Calculator

¹⁰⁸ COMET-VR 2.0 is a web-based tool that provides estimates of carbon sequestration and net greenhouse gas emissions from soils and biomass for US farms. It links databases containing information on soils, climate and management practices to run an ecosystem simulation model as well as empirical models for soil N₂O emissions and CO₂ from fuel usage for field operations. In 2011, an updated version was released - <http://www.comet2.colostate.edu/>. In 2014 the tool was updated to COMET FARM - <http://cometfarm.nrel.colostate.edu/>

¹⁰⁹ <http://surf.kbs.msu.edu/>

Differences in carbon soil sequestration rates between corn and soybeans can be explained by the greater plant matter residue contribution of the corn crop in the soybean-corn rotation. Research by Alvarez & Steinbach (2012) estimated that corn/maize contributes 7,178 Mg/ha/year of dry matter as crop residue compared to soybeans which contribute less (by 50%) at 3,373 Mg/ha/year.

In sum, drawing on these models and the literature discussed in Appendix 5, the analysis presented in the following sub-sections assumes the following:

US: In previous reports (up to 1996-2011) no differentiation was made between corn and soybeans. The assumptions used were based on research as discussed earlier and uses differences between NT and CT of 400 kg of carbon/ha/year of soil carbon sequestered (NT systems store 375 kg of carbon/ha/year; RT systems store 175 kg of carbon/ha/year; and CT systems store 25 kg of carbon/ha/year). In this report (and the previous three), the soil carbon sequestered by tillage system for corn in continuous rotation with soybeans is assumed to be a net sink of 250 kg of carbon/ha/year based on:

- NT systems store 251 kg of carbon/ha/year;
- RT systems store 75 kg of carbon/ha/year;
- CT systems store 1 kg of carbon/ha/year.

The soil carbon sequestered by tillage system for soybeans in a continuous rotation with corn is assumed to be a net sink of 100 kg of carbon/ha/year based on:

- NT systems release 45 kg of carbon/ha/year;
- RT systems release 115 kg of carbon/ha/year;
- CT systems release 145 kg of carbon/ha/year.

South America (Argentina, Brazil, Paraguay and Uruguay): soil carbon retention is 175 kg carbon/ha/year for NT soybean cropping and CT systems release 25 kg carbon/ha/year (a difference of 200 kg carbon/ha/year). In previous reports (up to 1996-2013) the difference used was 300 kg carbon/ha/year.

Where the use of biotech crops has resulted in a reduction in the number of spray passes or the consistent use of less intensive cultivation practices (less ploughing) this has provided (and continues to provide) a permanent reduction in carbon dioxide emissions.

4.2.3 Herbicide tolerance and conservation tillage

The adoption of GM HT crops has impacted on the type of herbicides applied, the method of application (foliar, broadcast, soil incorporated) and the number of herbicide applications. For example, the adoption of GM HT canola in North America has resulted in applications of residual soil-active herbicides being mostly replaced by post-emergence applications of broad-spectrum herbicides with foliar activity (Brimner *et al* (2004)). Similarly, in the case of GM HT cotton the use of glyphosate to control both grass and broadleaf weeds, post-emergent, largely replaced the use of soil residual herbicides applied pre- and post-emergence (McClelland *et al* (2000)). The

type and number of herbicide applications changed, sometimes (but often not) resulting in a reduction in the number of herbicide applications (see section 3).

In addition, there has been a shift from conventional tillage to reduced-till and no-till. This has had a marked effect on tractor fuel consumption due to energy-intensive cultivation methods being replaced with no/reduced tillage and largely herbicide-based weed control systems. The GM HT crop where this is most evident is GM HT soybeans. Here, adoption of the technology has made an important contribution to facilitating the adoption of reduced or no tillage farming¹¹⁰. Before the introduction of GM HT soybean cultivars, NT systems were practised by some farmers with varying degrees of success using a number of herbicides. The opportunity for growers to control weeds with a non-residual foliar herbicide as a “burn down” pre-seeding treatment, followed by a post-emergent treatment when the soybean crop became established, made the NT system more reliable, technically viable and commercially attractive. These technical and cost advantages have contributed to the rapid adoption of GM HT cultivars and a substantial increase in the NT soybean area in the US (also more than a seven-fold increase in Argentina). In both countries, GM HT soybeans are estimated to account for over 95% of the NT soybean crop area.

4.2.4 Herbicide tolerant soybeans

4.2.4.1 The US

The area of soybeans cultivated in the US has increased from 26 million ha in 1996 to 33.1 million ha in 2015. Over the same period, the soybean area planted using conventional tillage (CT) fell by 25% (from 7.5 million ha to 5.6 million ha), the area planted using RT¹¹¹ decreased by 23% (from 10.7 million ha to 8.3 million ha) and the area planted using NT increased by 149% (from 7.7 million ha to 19.2 million ha: Table 67).

The most rapid rate of adoption of the GM HT technology has been by farmers using NT systems (GM HT cultivars accounting for an estimated 99% of total NT soybeans by 1999). This compares with conventional tillage systems where GM HT cultivars account for 68% of total conventional tillage plantings (Table 67).

Table 67: US soybean: tillage practices and the adoption of GM HT cultivars 1996-2015 (million ha)

	Total area	No-till	Reduced till	Conventional till	Total GM HT area	Total conventional area (non-GM)	No till GM HT area	Reduced till GM HT area	Conventional tillage GM HT area
1996	25.98	7.72	10.75	7.51	0.49	25.49	0.37	0.11	0.01
1997	28.33	8.72	12.03	7.58	3.20	25.13	1.62	1.20	0.38
1998	29.14	9.28	12.69	7.17	11.78	17.36	8.52	2.54	0.72
1999	29.84	9.65	12.78	7.41	16.39	13.45	9.55	5.11	1.73
2000	30.15	9.90	12.69	7.56	18.21	11.94	9.80	5.71	2.70

¹¹⁰ See for example, CTIC 2002.

¹¹¹ Includes mulch and ridge till

2001	29.99	10.16	12.53	7.30	22.18	7.81	10.05	9.40	2.73
2002	29.55	10.31	12.26	6.98	24.28	5.27	10.20	11.03	3.05
2003	29.71	10.92	12.30	6.49	25.74	3.97	10.81	11.68	3.25
2004	30.28	11.69	12.51	6.08	27.20	3.08	11.57	11.88	3.75
2005	28.88	11.64	11.41	5.83	26.87	2.01	11.52	10.84	4.51
2006	30.56	12.84	11.52	6.20	27.20	3.36	12.71	11.06	3.43
2007	25.76	11.20	9.53	5.03	23.43	2.33	11.09	9.15	3.19
2008	30.20	13.59	10.66	5.95	27.79	2.41	13.47	10.24	4.08
2009	30.91	14.28	10.54	6.09	28.13	2.78	14.16	10.22	3.75
2010	31.56	14.99	10.89	5.68	29.35	2.21	14.89	10.56	3.90
2011	30.06	16.23	8.72	5.11	28.25	1.81	16.13	8.45	3.67
2012	30.82	17.26	8.32	5.24	28.67	2.15	17.17	8.16	3.34
2013	30.71	17.81	7.68	5.22	28.55	2.16	17.74	7.52	3.29
2014	33.43	19.39	8.36	5.68	31.42	2.01	19.33	8.19	3.90
2015	33.12	19.21	8.28	5.63	31.14	1.98	19.17	8.12	3.85

Source: Adapted from Conservation Tillage and Plant Biotechnology (CTIC) 1998, 2000, 2002, 2006, 2007 and 2008, GfK Kynetec, USDA-ERS ARMS (2016) Phase II soybean survey, No-Till Farmer Magazine (2016) 8th Annual Benchmarking Study 2015

Note: RT includes mulch and ridge till

The importance of GM HT soybeans in the adoption of a NT system has also been confirmed by an American Soybean Association (ASA) study (2001) of conservation tillage. This study found that the availability of GM HT soybeans facilitated and encouraged farmers to implement reduced tillage practices; a majority of growers surveyed indicated that GM HT soybean technology had been the factor of *greatest* influence in their adoption of reduced tillage practices.

a) Fuel consumption

Based on the soybean crop area planted by tillage system, type of seed planted (GM HT and conventional) and applying the fuel usage consumption rates presented in section 4.2.1, the total consumption of tractor fuel has increased by only 6.75% (64.2 million litres - 1996 to 2015: Table 68) while the area planted increased by 27.5%. Over the same period, the average fuel usage fell 16.3% (from 36.6 litres/ha to 30.7 litres/ha). A comparison of GM HT versus conventional production systems shows that in 2015, the average tillage fuel consumption on the GM HT planted area was 29.6 litres/ha compared to 47.6 litres/ha for the conventional crop.

Table 68: US soybean: consumption of tractor fuel used for tillage (1996-2015)

	Total fuel consumption (million litres)	Average (litre/ha)	Conventional average (litre/ha)	GM HT average (litres/ha)
1996	952.1	36.6	36.9	26.0
1997	1,027.0	36.2	36.9	31.4
1998	1,044.9	35.8	41.7	27.1
1999	1,067.9	35.8	42.9	30.0
2000	1,077.2	35.7	42.7	31.2
2001	1,064.2	35.5	44.5	32.3
2002	1,040.9	35.2	46.1	32.9
2003	1,032.1	34.7	46.7	32.9

2004	1,036.9	34.2	45.9	32.9
2005	980.9	34.0	44.4	33.2
2006	1,029.7	33.7	46.4	32.1
2007	859.6	33.4	46.1	32.1
2008	1,001.0	33.1	45.8	32.0
2009	1,018.0	32.9	46.7	31.6
2010	1,027.1	32.5	46.2	31.5
2011	942.2	31.4	46.0	30.4
2012	956.1	31.0	47.1	29.8
2013	942.1	30.7	47.4	29.4
2014	1,025.5	30.7	47.4	29.6
2015	1,016.3	30.7	47.6	29.6

The cumulative permanent reduction in tillage fuel use in US soybeans is summarised in Table 69. This amounted to a reduction in tillage fuel usage of 1,810 million litres which equates to a reduction in carbon dioxide emission of 4,831 million kg.

Table 69: US soybeans: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1996-2015)

	Annual reduction based on 1996 average (litres/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1996	0.00	25.98	0.00	0.00
1997	0.40	28.33	11.36	30.33
1998	0.80	29.15	23.38	62.41
1999	0.86	29.84	25.65	68.50
2000	0.92	30.15	27.66	73.86
2001	1.16	29.99	34.94	93.28
2002	1.41	29.54	41.72	111.39
2003	1.91	29.71	56.64	151.23
2004	2.40	30.28	72.69	194.09
2005	2.68	28.88	77.46	206.82
2006	2.96	30.56	90.46	241.52
2007	3.27	25.75	84.17	224.73
2008	3.51	30.21	106.06	283.19
2009	3.71	30.91	114.73	306.33
2010	4.11	31.56	129.58	345.99
2011	5.30	30.05	159.19	425.04
2012	5.63	30.82	173.59	463.49
2013	5.97	30.70	183.19	489.12
2014	5.97	33.42	199.42	532.46
2015	5.97	33.12	197.63	527.67
Total			1,809.53	4,831.45

Assumption: baseline fuel usage is the 1996 level of 36.6 litres/ha

b) Soil carbon sequestration

Based on the crop area planted by tillage system and type of seed planted (GM HT and conventional) and using estimates of the soil carbon sequestered by tillage system for corn and soybeans in continuous rotation; the soybean NT system is assumed to release 45 kg of carbon/ha/year; the RT system releases 115 kg carbon/ha/year; and the CT system releases 145 kg carbon/ha/year)¹¹².

Our estimates of total soil carbon sequestered for the US soybean crop over the 1996 to 2015 period are (Table 70):

- Although the area planted to soybeans has increased by 7.14 million ha, there has been a small aggregate decrease of 38.9 million kg carbon/year (a release of 2,672 million kg in 1996 compared to 2,633 million kg carbon/year in 2015);
- the average level of carbon released per ha decreased by 22.7% (23.4 kg carbon/ha/year) from 102.9 to 79.5 kg carbon/ha/year.

Table 70: US soybeans: potential soil carbon sequestration (1996 to 2015)

	Total carbon sequestered (million kg)	Average (kg carbon/ha/yr)
1996	- 2,672.23	-102.9
1997	- 2,874.83	-101.5
1998	- 2,917.27	-100.1
1999	- 2,978.15	-99.8
2000	- 3,000.83	-99.5
2001	- 2,957.01	-98.6
2002	- 2,884.96	-97.7
2003	- 2,846.80	-95.8
2004	- 2,845.91	-94.0
2005	- 2,680.60	-92.8
2006	- 2,801.18	-91.7
2007	- 2,328.83	-90.4
2008	- 2,700.74	-89.4
2009	- 2,737.44	-88.6
2010	- 2,750.50	-87.2
2011	- 2,473.26	-82.3
2012	- 2,493.59	-80.9
2013	- 2,440.95	-79.5
2014	- 2,657.22	-79.5
2015	- 2,633.35	-79.5

Cumulatively, since 1996 the increase in soil carbon sequestered due to the increase in RT and NT in US soybean production systems has been 6,933 million kg of carbon which, in terms of carbon dioxide emissions, equates to a saving of 25,444 million kg of carbon dioxide that would otherwise have been released into the atmosphere (Table 71). Readers should note that this

¹¹² The actual rate of soil carbon sequestered by tillage system is, however, dependent upon soil type, soil organic content, quantity and type of crop residue, so these estimates are indicative averages

estimate does not take into consideration the potential loss in carbon sequestration that may arise if some of the land using RT/NT is returned to conventional tillage.

Table 71: US soybeans: potential additional soil carbon sequestration (1996 to 2015)

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total additional carbon sequestered (million kg)	Total additional Carbon dioxide sequestered (million kg)
1996	0.0	26.0	0.00	0.00
1997	1.4	28.3	39.33	144.35
1998	2.8	29.1	80.93	297.02
1999	3.1	29.8	91.02	334.06
2000	3.3	30.1	100.23	367.85
2001	4.3	30.0	127.80	469.04
2002	5.2	29.5	153.56	563.58
2003	7.0	29.7	208.80	766.29
2004	8.9	30.3	268.21	984.34
2005	10.0	28.9	289.94	1,064.08
2006	11.2	30.6	342.60	1,257.35
2007	12.4	25.8	319.96	1,174.25
2008	13.5	30.2	406.34	1,491.28
2009	14.3	30.9	441.73	1,621.16
2010	15.7	31.6	495.86	1,819.80
2011	20.6	30.1	617.90	2,267.71
2012	22.0	30.8	676.92	2,484.29
2013	23.4	30.7	717.28	2,632.42
2014	23.4	33.4	780.83	2,865.65
2015	23.4	33.1	773.82	2,839.91
Total			6,933.08	25,444.41

Assumption: carbon sequestration remains at the 1996 level of -102.9 kg carbon/ha/year

4.2.4.2 Argentina

Since 1996, the area planted to soybeans in Argentina, has increased from 5.91 to 19.4 million ha (+228%). Over the same period, the area planted using NT practices also increased substantially from 2.15 to 17.27 million ha, whilst the area planted using conventional tillage decreased from 3.76 to 2.13 million ha (Table 72).

As in the US, a key driver for the growth in NT soybean production has been the availability of GM HT soybeans, which in 2015, accounted for 99.5% of the total Argentine soybean area. Finger *et al* (2009: based on a survey of Argentine soybean growers) identified that the combination of herbicide tolerance and NT were the key drivers to adoption of GM HT soybeans, facilitating easier crop management and reducing herbicide costs. As indicated in section 3, the availability of this technology has also provided an opportunity for growers to 'second crop soybeans' in a NT system with wheat. In the early to mid 1990s, 5%-10% of the total soybean crop was a second crop following on from wheat (in the same season). In the last ten years, the second crop soybean area has been significantly higher, within a range of 15%-30% of the total soybean area (the maximum each year influenced by the total area planted to wheat).

During the 1990s and early 2000s, NT stimulated an increase in the soybean-maize rotation which reduced insect pressure, restored soil organic matter (SOM), and increased crop residue input and nutrient cycling. Therefore, the use of maize and other cover crops in the soybean rotation has resulted in a more sustainable approach to soil management. Nevertheless, a soybean-soybean monoculture accounts for the majority of production mainly because of the relatively higher costs of growing maize and its greater vulnerability to drought (Wingeyer *et al*, (2015)).

It should also be noted that in the early 1990s, NT farming helped to reduce soil erosion by 90% (from about 10+ tonnes/ha of soil loss to about 1 tonne/ha), contributed to additional water accumulated in the top four inches (8.8 cm) of soil, contributed to higher crop yields of up to 11%, as well as reducing fuel use and labour costs (source: Argentine No-Till Farmers Association (AAPRESID) 2009).

Table 72: Argentine soybeans: tillage practices and the adoption of GM HT cultivars 1996-2015 (million ha)

	Total area	No-till (NT)	Conventional till (CT)	Total GM HT area	Total conventional area (non-GM)	NT GM HT area	CT GM HT area
1996	5.91	2.15	3.76	0.04	5.87	0.04	0.00
1997	6.40	2.87	3.53	1.76	4.64	1.76	0.00
1998	6.95	3.32	3.63	4.80	2.15	3.32	1.48
1999	8.18	3.78	4.40	6.64	1.54	3.78	2.86
2000	10.59	5.02	5.57	9.00	1.59	5.02	3.98
2001	11.50	6.66	4.84	10.93	0.57	6.66	4.27
2002	12.96	8.67	4.29	12.45	0.51	8.67	3.78
2003	13.50	9.78	3.72	13.23	0.27	9.78	3.45
2004	14.35	11.39	2.96	14.06	0.29	11.39	2.67
2005	15.20	11.54	3.66	14.95	0.25	11.54	3.41
2006	16.15	12.41	3.74	15.84	0.31	12.41	3.43
2007	16.59	13.56	3.03	16.42	0.17	13.56	2.86
2008	16.77	14.59	2.18	16.60	0.17	14.59	2.01
2009	18.60	15.83	2.77	18.18	0.42	15.83	2.35
2010	18.20	15.83	2.37	18.02	0.18	15.83	2.19
2011	18.60	16.55	2.05	18.41	0.19	16.55	1.86
2012	19.35	17.22	2.13	19.25	0.10	17.22	2.03
2013	19.75	17.58	2.17	19.65	0.10	17.58	2.07
2014	19.78	17.60	2.18	19.68	0.10	17.60	2.08
2015	19.40	17.27	2.13	19.30	0.10	17.27	2.03

Adapted from Benbrook, Trigo and AAPRESID (2012)

a) Fuel consumption

Between 1996 and 2015, total fuel consumption associated with soybean cultivation increased by 113% from 231.5 to 482.5 million litres/year. However, during this period, the average quantity of fuel used per ha fell 36% from 39.1 to 24.8 litres/ha, due mainly to the widespread adoption of GM HT soybean seed and NT systems. If the proportion of NT soybeans in 2015 (applicable to the total 2015 area planted) had remained at the 1996 level, an additional 3,218 million litres of

fuel would have been used. At this level of fuel usage, an additional 8,591 million kg of carbon dioxide would otherwise have been released into the atmosphere (Table 73).

Table 73: Argentine soybeans: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1996-2015)

	Annual reduction based on 1996 average of 39.1 (litres/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1996	0.0	5.9	0.0	0.00
1997	2.3	6.4	14.7	39.16
1998	3.1	7.0	21.5	57.39
1999	2.7	8.2	21.9	58.54
2000	3.0	10.6	31.6	84.45
2001	5.8	11.5	67.2	179.41
2002	8.3	13.0	107.3	286.57
2003	9.8	13.5	132.2	352.90
2004	11.7	14.3	167.4	447.02
2005	10.7	15.2	163.0	435.19
2006	11.0	16.2	177.4	473.74
2007	12.3	16.6	204.2	545.15
2008	13.7	16.8	230.4	615.13
2009	13.2	18.6	245.9	656.53
2010	13.7	18.2	249.8	667.06
2011	14.3	18.6	265.5	709.00
2012	14.3	19.4	276.3	737.59
2013	14.3	19.8	282.0	752.84
2014	14.3	19.8	282.4	753.98
2015	14.3	19.4	277.0	739.49
Total			3,217.7	8,591.1

Note: based on 21.89 litres/ha for NT and 49.01 litres/ha for CT

b) Soil carbon sequestration

Over the two decades to the late 1990s, soil degradation levels were reported to have increased in the humid and sub-humid regions of Argentina. The main cause of this was attributed to leaving land fallow following a wheat crop in a wheat/first soybean crop rotation. This resulted in soils being relatively free of weeds and crop residues but exposed to heavy summer rains which often led to extensive soil degradation and loss.

Research into ways of reducing soil degradation and loss was undertaken (mostly relating to the use of NT systems¹¹³) and this identified that NT systems could play an important role. As such, in the last twenty years, there has been an intensive programme of research and technology transfer targeted at encouraging Argentine growers to adopt NT systems.

¹¹³ Trials conducted by INTA found that direct sowing increases the yields of wheat and second soybean crop in rotation. Other benefits observed were: less soil inversion leaving a greater quantity of stubble on the surface, improvements in hydraulic conductivity, more efficient use of soil water, and higher soil organic matter contents.

Specific research into soil carbon sequestration in Argentina is limited. Fabrizzi *et al* (2003) indicated that a higher level of total organic carbon was retained in the soil with NT system compared with a CT system, but no quantification was provided. Detailed research by Steinbach (2006) modelled the impact on the conversion of the Argentinean Pampas to no-till to mitigate the global warming effect. This work estimated that NT conversion would result in an increase of soil organic carbon (SOC) of 74 million tonnes of carbon, about twice the annual carbon emissions from fossil fuel consumed in Argentina. However, the report concluded that the increased emissions of nitrous oxide might offset the carbon mitigation of no-till after 35 years. Derpsch *et al* (2010) estimates that two-thirds of the area under NT systems in South America is permanently in NT, which in Argentina is over 70% of the NT crop area. This suggests that these carbon sequestration gains are of a permanent nature.

Results from a 15-year experiment in the semi-arid Argentine Pampa to evaluate a combination of three tillage systems (no tillage, no tillage with cover crop in winter and reduced tillage) and two crop sequences (soybean–maize and soybean monoculture) concluded that NT tillage system had a greater impact on total organic carbon (TOC) stock than crop sequence (Alvarez *et al* (2014)). Total organic carbon stock, up to a depth of 100 cm showed significant differences between soils under different tillage systems (RT < NT = NT with cover crop), the last ones having 8% more than the RT treatment. Soybean–maize had 3% more organic carbon up to 100 cm depth than the soybean monoculture. Up to 100 cm depth, the NT treatments accumulated 333 kg TOC/ha/year more than RT, while the soybean-maize sequence accumulated only 133 kg TOC/ha/year more than soybean monoculture. At 0–30 cm depth, the NT treatments had 267 kg TOC/ha/year more than the RT treatment.

Applying a conservative estimate of soil carbon retention of 175 kg carbon/ha/yr for NT and a release of 25 kg carbon/ha/yr for CT soybean cropping in Argentina, a cumulative total of 23,729 million kg of carbon, which equates to a saving of 87,085 million kg of carbon dioxide, has been retained in the soil that would otherwise have been released into the atmosphere (Table 74).

Table 74: Argentine soybeans: potential additional soil carbon sequestration (1996 to 2015)

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total additional carbon sequestered (million kg)	Total additional Carbon dioxide sequestered (million kg)
1996	0.0	5.91	0.0	0.0
1997	16.92	6.39	108.17	396.98
1998	22.80	6.95	158.52	581.78
1999	19.77	8.18	161.68	593.38
2000	22.03	10.59	233.27	856.09
2001	43.09	11.50	495.53	1,818.58
2002	61.05	12.96	791.51	2,904.83
2003	72.20	13.50	974.71	3,577.19
2004	86.07	14.34	1,234.69	4,531.31
2005	79.08	15.20	1,202.00	4,411.35
2006	81.02	16.15	1,308.48	4,802.13
2007	90.79	16.59	1,505.72	5,526.00

2008	101.33	16.77	1,699.00	6,235.34
2009	97.49	18.60	1,813.37	6,655.06
2010	101.23	18.20	1,842.45	6,761.81
2011	105.28	18.60	1,958.28	7,186.90
2012	105.28	19.35	2,037.25	7,476.69
2013	105.28	19.75	2,079.36	7,631.25
2014	105.28	19.78	2,082.52	7,642.84
2015	105.28	19.40	2,042.51	7,496.01
Total			23,729.02	87,085.50

Assumption: NT = +175 kg carbon/ha/yr, Conventional Tillage CT = -25 kg carbon/ha/yr

4.2.4.3 Brazil

In earlier reports (up to 1996-2009), Brazil was excluded from the analysis of carbon savings associated with the facilitating role of GM HT soybeans on the adoption of NT/RT systems in the Brazilian soybean sector, largely because NT/RT systems were commonplace in the sector before the legal availability of GM HT soybeans in 2003. However, after consultation with several analysts in Brazil who have examined the factors influencing the adoption of NT/RT systems in Brazil, we have partially included some of the Brazilian GM HT soybean area in the calculations of carbon savings (included first in the report covering the period 1996-2010). This analysis includes the area devoted to GM HT soybeans in the southern states of Santa Catarina, Paraná and Rio Grande de Sol where the agricultural conditions are similar to those in Argentina and where the availability of GM HT soybean technology is considered to have played an important role in allowing farmers to adopt NT/RT systems.

From 1997 when GM HT soybeans were first planted in Brazil (illegally), the total area of GM HT soybeans has increased from 0.1 million ha to 31.3 million ha in 2015, of which these southern states accounted for 34.7% (10.85 million ha). The vast majority of soybean production in these states uses NT systems (90%: 10.39 million ha), with virtually all of the NT area being GM HT soybeans (Table 75).

Table 75: Southern Brazil (Santa Catarina, Parana and Rio Grande de Sol states) soybeans: tillage practices and the adoption of biotech cultivars 1997-2015 (million ha)

	Total area	No-till	Convention al tillage	Total GM HT area	Total conventional area (non-GM)	NT GM HT area	NT non- GM HT
1997	6.19	1.86	4.33	0.10	6.09	0.10	1.76
1998	6.12	2.14	3.98	0.50	5.62	0.50	1.64
1999	6.05	2.42	3.63	1.18	4.87	1.18	1.24
2000	5.98	2.69	3.29	1.30	4.68	1.30	1.39
2001	6.84	3.42	3.42	1.31	5.53	1.31	2.11
2002	7.49	4.12	3.37	1.74	5.75	1.74	2.38
2003	8.21	4.92	3.29	2.87	5.34	2.87	2.05
2004	8.59	5.58	3.01	3.01	5.58	3.01	2.57
2005	8.30	5.81	2.49	3.32	4.98	3.32	2.49
2006	8.25	6.19	2.06	5.36	2.89	5.36	0.83
2007	8.19	6.14	2.05	5.98	2.21	5.98	0.16

2008	8.23	6.58	1.65	6.09	2.14	6.09	0.49
2009	8.90	7.39	1.51	7.03	1.87	7.03	0.36
2010	9.13	7.76	1.37	7.67	1.46	7.67	0.09
2011	9.11	7.74	1.37	8.01	1.09	7.74	0.00
2012	9.88	8.60	1.28	8.90	0.98	8.60	0.00
2013	10.49	9.44	1.05	9.86	0.63	9.44	0.00
2014	11.07	9.97	1.10	10.41	0.66	9.97	0.00
2015	11.54	10.39	1.15	10.85	0.69	10.39	0.00

Adapted from FEBRAPDP, AMIS Global, CONAB and personal communications

NT = No-till

a) Fuel consumption

The Brazilian Federation of 'direct planting' (FEBRAPDP) and the Brazilian Agricultural Research Corporation (Embrapa) estimate that the conversion from CT to NT results in fuel savings of between 60%-70% (Plataforma Plantio Direto (2006)). This compares with a 55% reduction in the US (see section 4.2.4.1). In the analysis below, the more conservative fuel consumption rates used in the US (21.89 litres/ha for NT and 49.01 litres/ha for CT - a reduction of 55% for NT relative to CT) are applied to the GM HT soybean area planted in the three southern Brazilian states.

Total fuel consumption in soybean cultivation has increased by 7.7% from 253 to 283.9 million litres/year between 1997 and 2015. This increase in aggregate fuel use largely reflects the 86% increase in the area planted to soybeans in these three states during this period. However, the average quantity of fuel used per ha fell 39.8% from 40.9 to 24.6 litres/ha largely as a result of the adoption of GM HT technology and its facilitating role in the widespread change from CT to NT production methods. If the mix of tillage practices prevailing in 1997 (where CT dominated) were applicable in 2015 in the three southern states, an additional 1,779 million litres of fuel would have been used. At this level of fuel usage, an additional 4,749 million kg of carbon dioxide would otherwise have been released into the atmosphere (Table 76).

Table 76: Brazil (3 southernmost states) soybeans: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1997-2015)

	Annual reduction based on 1997 average of 40.9 (litres/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1997	0.00	6.19	0.00	0.00
1998	1.36	6.12	8.30	22.15
1999	2.71	6.05	16.40	43.80
2000	4.07	5.98	24.34	65.00
2001	5.42	6.84	37.09	99.03
2002	6.78	7.49	50.76	135.53
2003	8.14	8.21	66.83	178.43
2004	9.49	8.59	81.52	217.65
2005	10.85	8.30	89.98	240.26
2006	12.20	8.25	100.65	268.73
2007	12.20	8.19	99.89	266.71
2008	13.56	8.23	111.56	297.86
2009	14.37	8.90	127.94	341.60

2010	14.92	9.13	136.24	363.75
2011	14.92	9.11	135.83	362.66
2012	15.46	9.88	152.79	407.95
2013	16.27	10.49	170.74	455.87
2014	16.27	11.07	180.20	481.13
2015	16.27	11.54	187.77	501.35
Total			1,778.82	4,749.45

Note: based on 21.89 litres/ha for NT and RT and 49.01 litres/ha for CT

b) Soil carbon sequestration

The rate of carbon sequestration in Brazil has been researched by several analysts. Bayer *et al* (2006) estimated the mean rate of carbon sequestration in NT Brazilian tropical soils to be 350 kg carbon ha/year, similar to the 340 kg carbon/ha/year reported for soils from temperate regions, but lower than the 480 kg/ha/year estimated for southern Brazilian sub-tropical soils. Amado & Bayer (2008) estimated an average carbon sequestration rate of 170 kg carbon/ha/year (0.0 – 440 kg carbon/ha/year) for NT soils in the south (sub-tropical) and middle-west (tropical) regions of Brazil. The highest level of carbon sequestration (360 to 420 kg carbon/ha/year) occurs in intensive cropping systems because of relatively high crop residue levels in the maize/soybean rotation or where winter and summer cover crops are used.

Our analysis applies a conservative soil carbon retention value of 200 kg of carbon/ha/year for NT soybean relative to CT cropping in Brazil (as applied in Argentina), a cumulative total of 13,118 million kg of carbon (equal to a saving of 48,144 million kg of carbon dioxide) has been retained in the soil that would otherwise have been released into the atmosphere (Table 77).

Table 77: Brazil (3 southern most states) soybeans: potential additional soil carbon sequestration (1997 to 2015)

	Annual increase in carbon sequestered based on 1997 average (kg carbon/ha)	Crop area (million ha)	Total addition carbon sequestered (million kg)	Total addition Carbon dioxide sequestered (million kg)
1997	0.0	6.2	0.00	0.00
1998	10.0	6.1	61.19	224.57
1999	20.0	6.0	120.98	444.00
2000	30.0	6.0	179.52	658.84
2001	40.0	6.8	273.52	1,003.82
2002	50.0	7.5	374.35	1,373.86
2003	60.0	8.2	492.84	1,808.72
2004	70.0	8.6	601.16	2,206.26
2005	80.0	8.3	663.60	2,435.41
2006	90.0	8.2	742.23	2,723.98
2007	90.0	8.2	736.65	2,703.51
2008	100.0	8.2	822.70	3,019.31
2009	106.0	8.9	943.51	3,462.67
2010	110.0	9.1	1,004.69	3,687.19
2011	110.0	9.1	1,001.67	3,676.13

2012	114.0	9.9	1,126.76	4,135.23
2013	120.0	10.5	1,259.12	4,620.99
2014	120.0	11.1	1,328.89	4,877.03
2015	120.0	11.5	1,384.75	5,082.04
Total			13,118.13	48,143.55

Assumption: NT/RT = +175 kg carbon/ha/yr, CT = -25 kg carbon/ha/yr

4.2.4.4 Bolivia, Paraguay and Uruguay

NT systems have also become important in soybean production in Bolivia, Paraguay and Uruguay, where the majority of production in these countries use NT systems. Across the three countries, the area planted to soybeans has increased from 1.8 million ha to 5.68 million ha between 1999 and 2015 (Paraguay 1.17 to 3.4 million ha, Uruguay 8,900 ha to 1 million ha and Bolivia 0.63 to 1.28 million ha) and the area of GM soybeans from 58,000 ha to 5.2 million ha.

a) Fuel consumption

Using the findings and assumptions applied to Argentina¹¹⁴ (see above), the savings in fuel consumption for soybean production between 1999 and 2015 (associated with changes in no/reduced tillage systems, the adoption of GM HT technology and comparing the proportion of NT soybeans in 2015 with the 1999 level) has been 574 million litres. At this level of fuel saving, the reduction in the level of carbon dioxide released into the atmosphere has been 1,532 million kg.

b) Soil carbon sequestration

Applying the same rate of soil carbon retention for NT soybeans as Argentina, the cumulative increase in soil carbon since 1999, due to the increase in NT in Bolivia, Paraguay and Uruguay soybean production systems, has been 4,232 million kg of carbon. In terms of carbon dioxide emission this equates to a saving of 15,532 million kg of carbon dioxide that may otherwise have been released into the atmosphere.

4.2.4.5 Canada

During the period 1996 to 2008 period, tillage practices across the Canadian Prairies changed considerable with NT increasing from 15% to 51% of the crop prairie area (source: Agriculture Canada). Since 2009, the NT area accounted for between 52% and 55% of the tillage area, with the RT and CT shares being 17%-22% and 26%-28% respectively.

The introduction of GM HT soybeans in 1997 facilitated this transition as well as the doubling of the soybean crop area from 1.06 million ha in 1997 to 2.18 million ha in 2015. Within this, the NT soybean area increased five-fold from 0.21 million ha in 1997 to 1.2 million ha in 2015 whilst the RT area increased from 0.33 million ha to 0.37 million ha and the CT area increased from 0.52 million ha to 0.61 million ha.

¹¹⁴ We are not aware of any country-specific studies into NT/RT systems in these three countries. However, analysts consulted in each country have confirmed that the availability of GM HT technology in soybeans has been an important driver behind the use of NT/RT production systems. We have applied carbon change assumptions in these countries based on findings from Argentina because this represents the only available data from a neighbouring country. We acknowledge this represents a weakness to the analysis and the findings should be treated with caution.

a) Fuel consumption

Using the fuel saving assumption identified for US soybeans and applying these to Canada, the savings in fuel consumption for soybean production between 1997 and 2015 has been 158.5 million litres. At this level of fuel saving, the reduction in the level of carbon dioxide released into the atmosphere has been 423.2 million kg.

b) Soil carbon sequestration

Applying the same carbon sequestration assumptions used for US soybeans, the cumulative increase in soil carbon since 1997, due to the increase in NT soybean production systems, has been 601.6 million kg of carbon. In terms of carbon dioxide emission this equates to a saving of 2,207.9 million kg of carbon dioxide that may otherwise have been released into the atmosphere.

4.2.5 Herbicide tolerant maize

4.2.5.1 The US

The area of maize cultivated in the US has fluctuated over the last 20 years between 30.64 million ha (2001) and 37.88 million ha (2007); in 2015 it was 32.67million ha. Over the 1997-2015 period¹¹⁵, the maize area using conventional tillage (CT) fell by 29% (11.05 to 7.84 m ha), reduced tillage (RT) fell by 22% (15.57 to 12.09 m ha) and the no-till (NT) maize area increased by 129% (5.57 to 12.74 m ha: Table 78).

The most rapid rate of adoption of GM HT maize technology has been by growers using NT systems (GM HT cultivars accounted for an estimated 99% of total NT maize in 2015). This compares with conventional tillage systems for maize where GM HT cultivars account for about 63% of total maize plantings (Table 78).

Table 78: US maize: tillage practices and the adoption of GM HT cultivars 1997-2015 (million ha)

	Total area	No-till	Reduced till	Conventional till	Total GM HT area	Total conventional area (non GM)	No till GM HT area	Reduced till GM HT area	Conventional tillage GM HT area
1997	32.19	5.57	15.57	11.05	0.12	32.07	0.12	0.00	0.00
1998	32.44	5.95	13.32	13.17	1.66	30.78	1.19	0.47	0.00
1999	31.32	6.17	12.13	13.02	1.47	29.85	1.23	0.24	0.00
2000	32.19	6.77	11.73	13.69	2.25	29.94	1.69	0.56	0.00
2001	30.64	6.57	11.14	12.93	2.45	28.19	1.97	0.48	0.00
2002	31.93	6.98	11.59	13.36	3.83	28.10	3.14	0.68	0.01
2003	31.81	7.11	11.50	13.20	4.77	27.04	3.55	1.19	0.03
2004	32.47	7.42	11.69	13.36	6.50	25.97	4.64	1.79	0.07
2005	33.10	8.11	11.74	13.25	8.61	24.49	6.08	2.40	0.13
2006	31.70	8.28	11.08	12.34	11.41	20.29	7.85	2.94	0.62

¹¹⁵ GM HT maize was first planted commercially in the US in 1997. However, 1998 was the first year of widespread adoption of the technology

2007	37.88	10.22	13.87	13.79	19.70	18.18	9.71	8.61	1.38
2008	31.82	8.35	11.84	11.63	20.04	11.78	8.26	10.03	1.75
2009	32.21	9.58	11.92	10.71	21.90	10.31	9.49	10.90	1.51
2010	32.78	10.49	12.13	10.16	22.95	9.83	10.38	10.72	1.85
2011	34.35	11.68	12.71	9.96	24.73	9.62	11.56	11.21	1.96
2012	35.36	12.73	13.08	9.55	25.81	9.55	12.60	11.22	1.99
2013	35.48	13.13	13.13	9.22	30.16	5.32	13.00	12.37	4.79
2014	33.64	12.78	12.45	8.41	29.94	3.70	12.66	11.86	5.42
2015	32.68	12.75	12.09	7.84	29.07	3.59	12.62	11.51	4.94

Source: Adapted from Conservation Tillage and Plant Biotechnology (CTIC) 1998, 2000, 2002, 2006, 2007 and 2008, GfK Kynetec, USDA-ERS ARMS (2016), Phase II Soybean Survey, No-Till Farmer (2016) 8th annual benchmark study of tillage

Note: Reduced tillage includes mulch till and ridge till

a) Fuel consumption

Based on the maize crop area planted by tillage system, type of seed planted (biotech and conventional) and applying the fuel usage consumption rates presented in section 4.2.1 for maize, the total consumption of tractor fuel between 1997 and 2015 has decreased by 8.1% - 122.2 million litres: Table 79). Over the same period, the area planted to maize increased by 1.5%, highlighting a fall in average fuel usage of 9.4% (from 46.6 litres/ha to 42.2 litres/ha). A comparison of GM HT versus conventional production systems shows that in 2015, the average tillage fuel consumption on the GM HT planted area was 40.9 litres/ha compared to 52.4 litres/ha for the conventional crop.

Table 79: US maize: consumption of tractor fuel used for tillage (1997-2015)

	Total fuel consumption (million litres)	Average (litre/ha)	Conventional average (litre/ha)	GM HT average (litres/ha)
1997	1,501.2	46.6	46.7	30.1
1998	1,522.6	46.9	47.6	34.9
1999	1,465.0	46.8	47.5	32.8
2000	1,501.1	46.6	47.6	34.3
2001	1,425.5	46.5	47.7	33.4
2002	1,482.5	46.4	48.2	33.1
2003	1,473.5	46.3	48.4	34.4
2004	1,500.4	46.2	49.0	35.0
2005	1,517.7	45.9	49.6	35.2
2006	1,442.3	45.5	51.0	35.8
2007	1,710.8	45.2	51.6	39.2
2008	1,441.5	45.3	53.2	40.7
2009	1,431.8	44.5	53.5	40.2
2010	1,439.4	43.9	53.2	39.9
2011	1,491.6	43.4	53.0	39.7
2012	1,518.0	42.9	52.7	39.3
2013	1,514.4	42.7	52.8	40.9
2014	1,427.9	42.4	52.5	41.2
2015	1,379.0	42.2	52.4	40.9

The cumulative permanent reduction in tillage fuel use in US maize is summarised in Table 80. This amounted to a reduction in tillage fuel usage of 1,008 million litres which equates to a reduction in carbon dioxide emission of 2,693 million kg.

Table 80: US maize: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1997-2015)

	Annual reduction based on 1997 average (litres/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1997	0.00	32.19	0.00	0.00
1998	-0.30	32.44	-9.58	-25.57
1999	-0.14	31.32	-4.43	-11.84
2000	0.01	32.19	0.39	1.03
2001	0.11	30.64	3.30	8.81
2002	0.20	31.93	6.50	17.34
2003	0.31	31.81	10.00	26.71
2004	0.43	32.47	13.82	36.90
2005	0.78	33.10	25.85	69.01
2006	1.14	31.70	36.02	96.18
2007	1.47	37.88	55.82	149.05
2008	1.34	31.82	42.72	114.06
2009	2.18	32.21	70.34	187.80
2010	2.73	32.78	89.53	239.05
2011	3.22	34.35	110.60	295.29
2012	3.71	35.36	131.10	350.03
2013	3.95	35.48	140.20	374.33
2014	4.20	33.64	141.16	376.91
2015	4.44	32.68	145.09	387.39
Total			1,008.43	2,692.50

Assumption: baseline fuel usage is the 1997 level of 46.6 litres/ha

b) Soil carbon sequestration

Based on the crop area planted by tillage system and type of seed planted (GM HT and conventional) and using estimates of the soil carbon sequestered by tillage system for corn and soybeans in continuous rotation, the corn NT system is assumed to store 251 kg of carbon/ha/year, the RT system assumed to store 75 kg carbon/ha/year and the CT system assumed to store 1 kg carbon/ha/year)¹¹⁶, our estimates of total soil carbon sequestered are (Table 81):

- an increase of 1,536 million kg carbon/year (from 2,577 million kg in 1997 to 4,114 million kg carbon/year in 2015) due to a combination of an increase in the crop area and the NT corn area;

¹¹⁶ The actual rate of soil carbon sequestered by tillage system is, however, dependent upon soil type, soil organic content, quantity and type of crop residue

- the average amount of carbon sequestered per ha increased by 57.2% from 80.1 in 1997 to 125.9 kg carbon/ha/year in 2015.

Table 81: US maize: potential soil carbon sequestration (1997 to 2015)

	Total carbon sequestered (million kg)	Average (kg carbon/ha/yr)
1997	2,577.15	80.1
1998	2,506.56	77.3
1999	2,471.17	78.9
2000	2,593.19	80.5
2001	2,497.79	81.5
2002	2,634.48	82.5
2003	2,661.08	83.7
2004	2,753.20	84.8
2005	2,927.43	88.5
2006	2,919.69	92.1
2007	3,617.98	95.5
2008	2,996.31	94.2
2009	3,310.30	102.8
2010	3,552.94	108.4
2011	3,895.02	113.4
2012	4,185.92	118.4
2013	4,288.67	120.9
2014	4,151.08	123.4
2015	4,113.59	125.9

Cumulatively, since 1997 the increase in soil carbon due to the increase in RT and NT in US maize production systems has been 10,533 million kg of carbon which, in terms of carbon dioxide emissions, equates to a saving of 38,657 million kg of carbon dioxide that would otherwise have been released into the atmosphere (Table 82). This estimate does not take into consideration the potential loss in carbon sequestration that might arise from a return to conventional tillage.

Table 82: US maize: potential additional soil carbon sequestration (1997 to 2015)

	Annual increase in carbon sequestered based on 1997 average (kg carbon/ha)	Crop area (million ha)	Additional carbon sequestered (million kg)	Additional carbon dioxide sequestered (million kg)
1997	0.0	32.2	0.00	0.00
1998	-2.8	32.4	-90.93	-333.70
1999	-1.2	31.3	-36.32	-133.29
2000	0.5	32.2	15.56	57.11
2001	1.5	30.6	44.90	164.78
2002	2.4	31.9	78.15	286.81
2003	3.6	31.8	114.19	419.09
2004	4.7	32.5	153.64	563.84
2005	8.4	33.1	277.58	1,018.73

2006	12.0	31.7	381.73	1,400.94
2007	15.4	37.9	585.14	2,147.48
2008	14.1	31.8	448.24	1,645.05
2009	22.7	32.2	731.42	2,684.32
2010	28.3	32.8	928.21	3,406.54
2011	33.3	34.4	1,144.48	4,200.22
2012	38.3	35.4	1,354.80	4,972.11
2013	40.8	35.5	1,448.05	5,314.33
2014	43.3	33.6	1,457.30	5,348.30
2015	45.8	32.7	1,497.16	5,494.56
Total			10,533.30	38,657.22

Assumption: carbon sequestration remains at the 1997 level of 80.1 kg carbon/ha/year

4.2.5.2 Canada

Against the background of increasing adoption of NT and RT in the Canadian Prairies (see section 4.2.4.5) and a fluctuating maize area, the introduction and increasing adoption of GM HT maize technology (from 1999) has facilitated the doubling of the maize NT area from 0.34 million ha in 1999 to 0.722 million ha in 2015.

a) Fuel consumption

Using the US maize fuel saving assumptions (section 4.2.5.1), the saving in fuel consumption for Canadian maize production between 1999 and 2015 (associated with changes in RT/NT systems, the adoption of GM HT technology and comparing the proportion of NT corn in 2015 with the 1999 level) has been 83 million litres. This level of fuel saving is equal to a reduction in the level of carbon dioxide released into the atmosphere of 222 million kg.

b) Soil carbon sequestration

Applying the US carbon sequestrations assumptions for maize to the Canadian crop, the cumulative increase in soil carbon since 1999 has been 252 million kg of carbon. In terms of carbon dioxide emission savings, this equates to 926 million kg of carbon dioxide that may otherwise have been released into the atmosphere.

4.2.5.3 South America

In relation to both Argentina and Brazil it has not been possible to assess if the maize area in NT/RT has recently or is currently increasing due to the availability of GM HT maize because of a lack of relevant data and analysis. However, the following should be noted:

- in Argentina, GM HT maize was first available for use in 2004, yet has only become widely adopted in recent years (64% of 2015 crop used the technology). Therefore, it is unlikely that the availability of GM HT technology has played a significant role in the development of NT/RT farming in the Argentine maize crop;
- in Brazil, GM HT maize was first adopted on a widespread basis in 2011. Therefore, any increase in the use of NT/RT in the maize sector up to this date cannot be attributed to any facilitating role of the technology.

4.2.6 Herbicide tolerant canola

The analysis presented below relates to Canada only and does not include the US GM HT canola crop as the area devoted to canola in the US is relatively small by comparison to the area in Canada (0.69 million ha in the US in 2015 compared to 8.08 million ha in Canada).

Smyth *et al* (2011) surveyed 600 canola farmers in the three prairie provinces of Western Canada in the years 2007-2009, to evaluate the environmental impacts of the adoption of HT canola. As well as a reduction in the total number of herbicide applications (resulting in a decrease of herbicide active ingredient being applied), there were fewer tillage passes, improving moisture conservation, decreasing soil erosion and a substantial contribution to carbon sequestration in annual cropland. This research estimated that, by 2009, approximately 1 million tonnes of carbon (3.67 million tonnes of carbon dioxide) had either been sequestered or no longer released under land management systems facilitated by HT canola production, as compared to 1995.

Awada L *et al* (2014) identified that conservation tillage, notably NT, became profitable for, and popular with, the majority of Canadian arable farmers during and after the late 1990s and attributed an important role in the adoption of NT to the availability of GM HT canola. The increased use of NT contributed to a significant decrease in the area under summer fallow and to the increase in the area sown to canola and pulse crops. These changes contributed to the reduction of land degradation and to decreases in greenhouse gas (GHG) emissions.

a) Fuel consumption

Our estimate for the cumulative, permanent reduction in tillage fuel use in Canadian canola for the period 1996-2015 is 683.5 million litres, which equates to a reduction in carbon dioxide emissions of 1,825 million kg (Table 83).

Table 83: Canadian canola: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1996-2015)

	Annual reduction based on 1996 average 30.6 (l/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1996	0.0	3.5	0.0	0.00
1997	0.9	4.9	4.3	11.51
1998	0.9	5.4	4.8	12.83
1999	0.9	5.6	4.9	13.15
2000	0.9	4.9	4.3	11.48
2001	1.8	3.8	6.7	17.89
2002	2.7	3.3	8.7	23.12
2003	3.5	4.7	16.6	44.32
2004	4.4	4.9	21.9	58.35
2005	5.3	5.5	29.2	77.85
2006	6.2	5.2	32.5	86.64
2007	6.5	5.9	38.7	103.36
2008	7.1	6.5	46.0	122.77
2009	8.0	6.4	50.8	135.59
2010	8.8	6.5	57.7	153.93
2011	8.9	7.5	66.1	176.54
2012	8.9	8.6	76.0	202.86

2013	8.9	7.8	69.1	184.61
2014	8.9	8.3	73.8	197.16
2015	8.9	8.1	71.5	191.00
Total			683.5	1,825.00

Note fuel usage NT/RT = 17.3 litres/ha CT = 35 litres/ha

b) Soil carbon sequestration

The analysis of soil carbon sequestration levels associated with GM HT canola in Canada is based on the carbon sequestration co-efficient/assumptions derived by McConkey *et al* (2007). Table 84 summarises this analysis and shows a cumulative increase in soil carbon storage, associated with the increase in RT and NT in Canadian canola production between 1996 and 2015, of 2,510 million kg of carbon, which in terms of carbon dioxide emissions, equates to a saving of 9,212 million kg of carbon dioxide that would otherwise have been released into the atmosphere. Readers should note these estimates are based on a soil sequestration rate of 55 kg carbon/ha/year (based on McConkey *et al* (2007)) which is significantly lower than the rate used in the US for corn (250 kg carbon/ha/year) due to a combination of lower temperatures and different soil types in the Canadian canola growing regions compared to the US corn-soybean production belt.

Table 84: Canadian canola: potential additional soil carbon sequestration (1996 to 2015)

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total carbon sequestered (million kg)	Carbon dioxide (million kg)
1996	0.0	3.5	0.00	0.00
1997	3.3	4.9	15.83	58.09
1998	3.3	5.4	17.64	64.75
1999	3.3	5.6	18.08	66.37
2000	3.3	4.9	15.79	57.96
2001	6.5	3.8	24.60	90.30
2002	9.8	3.3	31.80	116.71
2003	13.0	4.7	60.96	223.72
2004	16.3	4.9	80.26	294.55
2005	19.5	5.5	107.07	392.96
2006	22.8	5.2	119.17	437.36
2007	24.1	5.9	142.16	521.72
2008	26.0	6.5	168.86	619.71
2009	29.3	6.4	186.50	684.44
2010	32.5	6.5	211.72	777.00
2011	32.5	7.5	242.81	891.10
2012	32.5	8.6	279.01	1,023.98
2013	32.5	7.8	253.91	931.84
2014	32.5	8.3	271.18	995.23
2015	32.5	8.1	262.70	964.10
Total			2,510.05	9,211.89

Notes: NT/RT = +55 kg of carbon/ha/yr CT = -10 kg of carbon/ha/yr

4.2.7 Herbicide tolerant cotton

The contribution to reduced levels of carbon sequestration arising from the adoption of GM HT cotton is likely to have been marginal and hence no assessments are presented. Although the area of NT cotton has increased significantly in countries such as the US, it still only represented 23.7% of the total cotton crop in 2009¹¹⁷. Therefore, no analysis has been undertaken relating to possible fuel usage and soil carbon sequestration savings associated with the adoption of GM HT cotton in the US. However, the importance of GM HT cotton in facilitating NT cotton tillage has been confirmed by Doane Marketing Research (2002) which identified the availability of GM HT cotton as a key driver for the adoption of NT production practices.

4.2.8 Insect resistant cotton

The cultivation of GM IR cotton has resulted in a significant reduction in the number of insecticide spray applications. Between 1996 and 2015, the global cotton area planted with GM IR cultivars increased from 0.77 million ha to 22.04 million ha. Based on a conservative estimate of four fewer insecticide sprays being required for the cultivation of GM IR cotton relative to conventional cotton, and applying this to the relevant global area (excluding Burkina Faso, China, Pakistan, Myanmar, Sudan and India¹¹⁸) of GM IR cotton over the period 1996-2015, suggests that there has been a reduction of 232 million ha of cotton 'spray' area. The resulting cumulative saving in tractor fuel consumption has been 195 million litres. This represents a permanent reduction in carbon dioxide emissions of 520 million kg (Table 85).

Table 85: Permanent reduction in global tractor fuel consumption and carbon dioxide emissions resulting from the cultivation of GM IR cotton (1996-2015)

	Total cotton area in GM IR growing countries excluding Burkina Faso, India, Pakistan, Myanmar, Sudan and China (million ha)	GM IR area excluding Burkina Faso, India, Pakistan, Myanmar, Sudan and China (million ha)	Total spray runs saved (million ha)	Fuel saving (million litres)	CO2 emissions saved (million kg)
1996	6.64	0.86	3.45	2.90	7.73
1997	6.35	0.92	3.67	3.09	8.24
1998	7.20	1.05	4.20	3.53	9.43
1999	7.42	2.11	8.44	7.09	18.92
2000	7.29	2.43	9.72	8.17	21.81
2001	7.25	2.55	10.18	8.55	22.84
2002	6.36	2.17	8.69	7.30	19.49
2003	5.34	2.17	8.70	7.30	19.50
2004	6.03	2.79	11.17	9.38	25.05
2005	6.34	3.21	12.84	10.78	28.79
2006	7.90	3.94	15.75	13.23	35.33
2007	6.07	3.25	12.99	10.91	29.14
2008	4.51	2.54	10.16	8.53	22.78

¹¹⁷ 2009 is the latest year for which no tillage data in cotton is available

¹¹⁸ Excluded because all spraying is assumed to be undertaken by hand

2009	5.33	2.96	11.83	9.94	26.54
2010	7.13	4.59	18.37	15.43	41.21
2011	6.61	4.43	17.70	14.87	39.71
2012	5.72	4.07	16.30	13.69	36.55
2013	5.29	3.75	15.01	12.61	33.66
2014	5.57	4.20	16.80	14.11	37.67
2015	5.00	3.95	15.78	13.26	35.40
Total			231.75	194.67	519.78

Notes: assumptions: 4 tractor passes per ha, 0.84 litres/ha of fuel per insecticide application

4.2.9 Insect resistant maize

Limited analysis of the possible contribution to reduced levels of carbon sequestration from the adoption of GM IR maize (via fewer insecticide spray runs) is presented. This is because the impact of IR maize adoption on carbon sequestration is likely to have been small for the following reasons:

- in some countries (eg, Argentina, Philippines) insecticide use for the control of pests targeted by the technology (eg, corn borer pests) has traditionally been negligible;
- even in countries where insecticide use for the control of relevant pests targeted by the technology has been practised, the share of the total crop treated has been limited (eg, in the US about 10% and 30% respectively of the crop treated for corn borer and rootworm pests);
- Control practices for CRW in the US often includes the application of insecticides via seed dressing.

4.2.9.1 Brazil

The impact of using GM IR maize in Brazil (since 2008) has resulted in farmers reducing the average number of insecticide spray runs by three (from five to two). This equates to a cut of 208 million ha of maize being sprayed in the eight years 2008-2015, with a cumulative saving in tractor fuel of 175 million litres. This is equivalent to a permanent reduction in carbon dioxide emissions of 467 million kg.

4.2.9.2 US, Canada, South Africa and Spain

Our estimates of the fuel and carbon dioxide savings associated with reduced application of insecticides with GM IR maize in these countries is based on historic patterns of insecticide application and therefore limited to:

- A maximum area equal to the lower of the GM IR area or 10% of the total crop in the US, Canada and Spain;
- The lower of the GM IR area (2.4 million ha in 2015) or 1.7 million ha in South Africa.

Assuming that there has been an average saving of one insecticide spray run on these areas each year since adoption of the technology, this equates to a reduction in the area sprayed over the 1996 to 2015 period of 81.8 million 'spray' ha. The resultant, cumulative saving in tractor fuel equates to 68.7 million litres, equivalent to a permanent reduction in carbon dioxide emissions of 183 million kg.

4.2.10 Insect resistant soybeans

IR soybean technology was first used commercially in South America in 2013, and in 2015 was planted on 12.8 million ha in Argentina, Brazil, Paraguay and Uruguay. The adoption of this technology has enabled farmers to reduce the average number of insecticide spray applications per ha by four in Brazil, two in Paraguay and one each in Argentina and Uruguay. The cumulative saving in tractor fuel use over this three-year period has, therefore been equal to 69.5 million litres, equivalent to a permanent reduction in carbon dioxide emissions of 186 million kg.

4.2.11 Intensification of crop production

As well as the adoption of GM technology facilitating the reduction in level of greenhouse gas emissions via reduced fuel use and additional soil carbon sequestration, the technology also delivers GHG emission benefits via the improvements in crop production. As indicated in section 3, the adoption of GM technology has resulted in additional production from a combination of higher yields and facilitation of second cropping of soybeans after a wheat crop in South America.

Estimating the possible GHG emissions savings associated with this additional production is, however, difficult due to the complex array of variables that impact on this and which vary by location. As such, no estimates are provided in this report. Nevertheless, the following points are important to recognise in furthering the debate about the potential GHG emission impacts associated with the use of GM crops and intensification of production:

- Higher yielding crops assimilate more carbon dioxide into carbohydrate, oxygen and water than lower yielding crops. Based on Lohry (1998) and applying to the 2015 level of additional global corn production (40.3 million tonnes) due to GM cultivars, this additional production assimilated about 136 million tonnes of carbon dioxide (which was converted by photosynthesis, sunlight, nutrients and water into oxygen and grain);
- Increasing crop yields result in an increase in carbon inputs from crop residues into soils which have a positive effect on soil carbon stocks (Berntsen *et al* (2006));
- Improved yields and additional production from second cropping (of soybeans in South America) effectively 'replaces' the need to extend crop production into new lands (which will require the switching of land uses from other crops, grazing land and/or non-agricultural land converted into cropping of soybeans, corn, cotton and canola). Where this land that would otherwise have been brought into agriculture remains in alternative uses that sequester important levels of GHGs (eg, forestry), it is likely that the net effect on GHG emissions is positive;
- Intensification of production is crucial if new land is not to be brought into production. For example, analysis by Tilman *et al* (2011) into meeting projected global food demand by 2050 suggests that moderate intensification delivers significant (three-fold) greenhouse gas emission savings compared to a scenario of no additional intensification.
- A question often posed about GHG emissions and more intensive agriculture is the scope for additional usage of nitrogen resulting in higher levels of nitric oxide emissions more than offsetting any carbon gains. Researchers such as Burney *et al* (2010¹¹⁹) have, however, concluded that intensification of agriculture leads to a net reduction in GHG

¹¹⁹ Albeit examining the impact on GHG emissions from general intensification of agriculture between 1961 and 2005

emissions even though fertiliser production and application tends to increase. A meta-analysis of 19 independent studies by Van Groenigen *et al* (2011) also concluded that the aims of optimal agricultural production and low GHG emissions are consistent and deliverable. In particular, emissions of nitrous oxide should be assessed as a function of crop nitrogen uptake and crop yield with nitrous oxide emissions tending to be stable in respect of yield levels provided nitrogen is applied efficiently and without waste. In addition, Katterera *et al* (2012) estimated that soil carbon stocks can increase by between 1kg-2kg of carbon for each kg of nitrogen fertiliser applied, with extensive production systems tending to result in lower soil carbon stocks than more intensively managed land.

Overall, the GHG emission savings arising from both the direct impact and facilitating role of GM technology (plus the productivity enhancing impact of the technology) 'fits' well with the global need to sustainably intensify production systems.

4.2.12 Summary of carbon sequestration impact

A summary of the carbon sequestration impact is presented in Table 86. This shows the following key points:

- The permanent savings in carbon dioxide emissions (arising from reduced fuel use of 9,823 million litres of fuel) since 1996 have been about 26,221 million kg;
- The additional amount of soil carbon sequestered since 1996 has been equivalent to 227,208 million kg of carbon dioxide that has not been released into the global atmosphere¹²⁰. The reader should note that these soil carbon savings are based on savings arising from the rapid adoption of NT/RT farming systems in North and South America (Argentina and Southern Brazil), for which the availability of GM HT technology has been cited by many farmers as an important facilitator. GM HT technology has therefore probably been an important contributor to this increase in soil carbon sequestration, but is not the only factor of influence. Other influences such as the availability of relatively cheap generic glyphosate (the real price of glyphosate fell threefold between 1995 and 2000 once patent protection for the product expired) have also been important. Cumulatively, the amount of carbon sequestered may be higher than these estimates due to year-on-year benefits to soil quality; however, it is equally likely that the total cumulative soil sequestration gains have been lower because only a proportion of the crop area will have remained in NT/RT. For example, in 2015 the NT/RT data from the US shows that 83% of the soybean crop (27.5 million ha) is typically using NT/RT, whilst 76% of the maize crop (24.8 million ha) derives from NT/RT. Given that the soybean: corn rotation is a common system in the US (though not the only system of production for either crop), this suggests that an important area in RT/NT one year (whilst planted to maize) remain in NT the next year for a following soybean crop. The estimate of 227,208 million kg of carbon dioxide not released into the atmosphere

¹²⁰ These estimates are based on fairly conservative assumptions and therefore the true values could be higher. Also, some of the additional soil carbon sequestration gains from RT/NT systems may be lost if subsequent ploughing of the land occurs. Estimating the possible losses that may arise from subsequent ploughing would be complex and difficult to undertake. This factor should be taken into account when using the estimates presented in this section of the report

should be treated with caution. It is a theoretical potential, with the actual level of carbon dioxide savings occurring across a probable wide variation.

Table 86: Summary of carbon sequestration impact 1996-2015

Crop/trait/country	Permanent fuel saving (million litres)	Potential carbon dioxide saving from reduced fuel use (million kg)	Potential carbon dioxide saving from soil carbon sequestration (million kg)
HT soybeans			
Argentina	3,218	8,591	87,085
Brazil	1,779	4,749	48,144
Bolivia, Paraguay, Uruguay	574	1,532	15,532
US	1,810	4,831	25,444
Canada	158	423	2,208
HT maize			
US	1,008	2,692	38,657
Canada	83	222	926
HT canola			
Canada	684	1,825	9,212
IR maize			
Brazil	175	467	0
USA, Canada, South Africa, Spain	69	183	0
IR cotton			
Global	195	520	0
IR soybeans			
Argentina, Brazil, Paraguay, Uruguay	70	186	0
Total	9,823	26,221	227,208

Note IR soybeans = savings from reduced insecticide use. All other savings associated with the HT stack in 'Intacta' soybeans included under HT soybeans

Examining further the context of the carbon sequestration benefits, Table 87 measures the carbon dioxide equivalent savings associated with planting of biotech crops for the latest year (2015), in terms of the number of car use equivalents. This shows that in 2015, the permanent carbon dioxide savings from reduced fuel use (2,819 million kg carbon dioxide) was the equivalent of removing 1.25 million cars from the road for a year and the additional soil carbon sequestration gains (23,900 million kg carbon dioxide) were equivalent to removing 10.62 million cars from the roads. In total, biotech crop-related carbon dioxide emission savings in 2015 were equal to the removal from the roads of 11.88 million cars, equal to 41% of all registered cars in the UK.

Table 87: Context of carbon sequestration impact 2015: car equivalents

Crop/trait/country	Permanent carbon dioxide savings arising from reduced fuel use (million kg of carbon dioxide)	Permanent fuel savings: as average family car equivalents removed from the road for a year ('000s)	Potential additional soil carbon sequestration savings (million kg of carbon dioxide)	Soil carbon sequestration savings: as average family car equivalents removed from the road for a year ('000s)
HT soybeans				
Argentina	739	329	7,496	3,332
Brazil	501	223	5,082	2,259
Bolivia, Paraguay, Uruguay	170	75	1,722	765
US	528	235	2,840	1,262
Canada	47	21	247	110
HT maize				
US	387	172	5,495	2,442
Canada	19	8	54	24
HT canola				
Canada	191	85	964	428
IR maize				
Brazil	83	37	0	0
USA, Canada, South.Africa, Spain	11	5	0	0
IR cotton				
Global	35	16	0	0
IR soybeans				
South.America	108	48	0	0
Total	2,819	1,254	23,900	10,622

Note IR soybeans = savings from reduced insecticide use. All other savings associated with the HT stack in 'Intacta' soybeans included under HT soybeans

Due to the limitations referred to above, no estimate of cumulative (1996-2015) carbon dioxide savings as car-equivalents has been provided.

Appendix 1: 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 (2015)

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	0.859	3,206	2,754	2,693	513	+10%	0.792	2,346	406
China	1.58	3,100	4,898	2,976	124	+10%	1.442	4,721	179

Note: Figures subject to rounding

Appendix 2: Impacts, assumptions, rationale and sources for all trait/country combinations

Country	Yield impact assumption used	Rationale	Yield references	Cost of technology data/assumptions	Cost savings (excluding impact of seed premium) assumptions
GM IR corn: resistant to corn boring pests					
US & Canada	+7% all years	Broad average of impact identified from several studies/papers and latest review/analysis covering 1996-2010 period	Carpenter & Gianessi (2002) found yield impacts of +9.4% 1997, +3% 1998, +2.5% 1999 Marra et al (2002) average impact of +5.04% 1997-2000 based a review of five studies, James (2003) average impact of +5.2% 1996-2002, Sankala & Blumenthal (2003 & 2006) range of +3.1% to +9.9%. Hutchison et al (2010) +7% examining impact over the period 1996-2010. Canada - no studies identified – as US - impacts qualitatively confirmed by industry sources (annual personal communications)	As identified in studies to 2008 and onwards based on weighted seed premia according to sale of seed sold as single and stacked traited seed	As identified in studies to 2005 and in subsequent year adjusted to reflect broad cost of 'foregone' insecticide use
Argentina	+9% all years to 2004, +5.5% 2005 onwards	Average of reported impacts in first seven years, later revised downwards for more recent years to reflect professional opinion	James (2003) cites two unpublished industry survey reports; one for 1996-1999 showing an average yield gain of +10% and one for 2000-2003 showing a yield gain of +8%, Trigo (2002) Trigo & Cap (2006) +10%, Trigo (2007 & 2008) personal communication estimates average yield impact since 2005 to be lower at between +5% and +6%	Cost of technology drawn from Trigo (2002) and Trigo & Cap (2006), ie, costed/priced at same level as US From 2007 based on Trigo and industry personal communications	None as maize crops not traditionally treated with insecticides for corn boring pest damage
Philippines	+24.6% to 2006,	Average of three	Gonzales (2005) found average yield impact of	Based on Gonzales (2005) &	Based on Gonzales (2005) & Gonzales (2009)

	2007 onwards +18%	studies used all years to 2006. Thereafter based on Gonzales et al (2009 ¹⁸)	+23% dry season crops & +20% wet season crops; Yorobe (2004) +38% dry season crops & +35% wet season crops; Ramon (2005) found +15.3% dry season crops & +13.3% wet season crops. Gonzales et al (2009) +18%	Gonzales (2009) – the only sources to break down these costs. Seed premia from 2012 based on weighted cost of seed sold as single and stacked traits	
South Africa	+11% 2000 & 2001 +32% 2002 +16% 2003 +5% 2004 +15% 2005-2007, +10.6% 2008 onwards	Reported average impacts used for years available (2000-2004), 2005-2007 based on average of other years. 2008 onwards based on Van der Welt (2009)	Gouse et al (2005), Gouse et al (2006 a) & b) reported yield impacts as shown (range of +11% to +32%), Van der Wald (2010)	Based on the same papers as used for yield, plus confirmation in 2006-2011 that these are representative values from industry sources	Sources as for cost of technology
Spain	+6.3% 1998-2004 +10% 2005-2008. 2009 onwards +12.6%	Impact based on authors own detailed, representative analysis for period 1998-2002 then updated to reflect improved technology based on industry analysis. From 2009 based on Riesgo et al (2012)	Brookes (2003) identified an average of +6.3% using the Bt 176 trait mainly used in the period 1998-2004 (range +1% to +40% for the period 1998-2002). From 2005, 10% used based on Brookes (2008) which derived from industry (unpublished sources) commercial scale trials and monitoring of impact of the newer, dominant trait Mon 810 in the period 2003-2007. Gomez Barbero & Rodriguez-Corejo (2006) reported an average impact of +5% for Bt 176 used in 2002-2004. Riesgo et al (2012) +12.6% identified as average yield gain	Based on Brookes (2003) the only source to break down these costs. The more recent cost of technology derive from industry sources (reflecting the use of Mon 810 technology). Industry sources also confirm value for insecticide cost savings as being representative. From 2009, based on Riesgo et al (2012)	Sources as for cost of technology

Other EU	France +10%, Germany +4%, Portugal +12.5%, Czech Republic +10%, Slovakia +12.3%, Poland +12.5%, Romania +7.1% 2007, +9.6% 2008 & +4.8% 2009 onward	Impacts based on average of available impact data in each country	Based on Brookes (2008) which drew on a number of sources. For France 4 sources with average yield impacts of +5% to +17%, for Germany the sole source had average annual impacts of +3.5% and +9.5% over a two year period, for Czech Republic three studies identified average impacts in 2005 of an average of 10% and a range of +5% to +20%; for Portugal, commercial trial and plot monitoring reported +12% in 2005 and between +8% and +17% in 2006; in Slovakia based on trials for 2003-2007 and 2006/07 plantings with yield gains averaging between +10% and +14.7%; in Poland based on variety trial tests 2005 and commercial trials 2006 which had a range of +2% to +26%; Romania based on reported impact by industry sources	Data derived from the same source(s) referred to for yield	Data derived from the same source(s) referred to for yield
Uruguay	As Argentina	As Argentina	No country-specific studies identified, so impact analysis from nearest country of relevance (Argentina) applied	As Argentina	As Argentina
Paraguay	As Argentina	As Argentina	No country-specific studies identified, so impact analysis from nearest country of relevance (Argentina) applied	As Argentina	As Argentina
Brazil	+4.66% 2008, +7.3% 2009 & 2010, +20.1% 2011, +14.6% 2012,	Farmer surveys	Galvão A (2009, 2010, 2012, 2013, 2014)	Data derived from the same references as cited for yield impacts. Seed premium based on weighted average of seed sales	Data derived from the same references as cited for yield impacts

	+11.1% 2013-2015				
Honduras	+13% 2003-2006 +24% 2007 onward	Trials results 2002 and farmer survey findings in 2007-2008	James (2003) cited trials results for 2002 with a 13% yield increase Falk Zepeda J et al (2009 and 2012) +24%	A proxy seed premium of \$30/ha used during trials (to 2005) based on seed premia in S Africa and the Philippines. From 2006 when commercialised based on industry sources	Nil – no insecticide assumed to be used on conventional crops
Colombia	+22%	Mendez et al (2011)	Mendez et al (2011) farm survey from 2009	Mendez et al (2011)	Mendez et al (2011)
GM IR corn (resistant to corn rootworm)	Yield impact assumption used	Rationale	Yield references	Cost of technology data/assumptions	Cost savings (excluding impact of seed premium) assumptions
US & Canada	+5% all years	Based on the impact used by the references cited	Sankala & Blumenthal (2003 & 2006) used +5% in analysis citing this as conservative, themselves having cited impacts of +12%–+19% in 2005 in Iowa, +26% in Illinois in 2005 and +4%–+8% in Illinois in 2004. Johnson S & Strom S (2008) used the same basis as Sankala & Blumenthal Rice (2004) range of +1.4% to +4.5% (based on trials) Canada - no studies identified – as US - impacts qualitatively confirmed by industry sources (personal communications 2005, 2007 & 2010)	Data derived from Sankala & Blumenthal (2006) and Johnson S & Strom S (2008). Seed costs 2008 onwards based on weighted seed sales of single and stacked traits Canada - no studies identified – as US - impacts qualitatively confirmed by industry sources	As identified in studies to 2005 and in subsequent year adjusted to reflect broad cost of ‘foregone’ insecticide use
IR cotton	Yield impact assumption used	Rationale	Yield references	Cost of technology data/assumptions	Cost savings (excluding impact of seed premium) assumptions
US	+9% 1996-2002 +11% 2003 & 2004 +10% 2005 onwards	Based on the (conservative) impact used by the	Sankala & Blumenthal (2003 & (2006) drew on earlier work from Carpenter and Gianessi (2002) in which they estimated the average	Data derived from the same sources referred to for yield and updated from 2008 based on industry	As identified in yield study references and in subsequent years adjusted to reflect broad cost of ‘foregone’ insecticide use

		references cited	yield benefit in the 1996-2000 period was +9%. Marra et al (2002) examined the findings of over 40 state-specific studies covering the period 1996 up to 2000, the approximate average yield impact was +11%. The lower of these two values was used for the period to 2002. The higher values applied from 2003 reflect values used by Sankala & Blumenthal (2006) and Johnson & Strom (2008) that take into account the increasing use of Bollgard II technology, and draws on work by Mullins & Hudson (2004) that identified a yield gain of +12% relative to conventional cotton. The values applied 2005 onwards were adjusted downwards to reflect the fact that some of the GM IR cotton area has still been planted to Bollgard I	sources (for the estimated share of the insect resistance trait in the total seed premia for stacked traired seed	
China	+8% 1997-2001 +10% 2002 onwards	Average of studies used to 2001. Increase to 10% on basis of industry assessments of impact and reporting of unpublished work by Schuchan	Pray et al (2002) surveyed farm level impact for the years 1999-2001 and identified yield impacts of +5.8% in 1999, +8% in 2000 and +10.9% in 2001 Monsanto China personal communications (2007-2014)	Data derived from the same sources referred to for yield	Data derived from the same sources referred to for yield
Australia	None	Studies have usually identified no	Fitt (2001) Doyle (2005) James (2002) CSIRO (2005)	Data derived from the same sources referred to for yield covering earlier years of	Data derived from the same sources referred to for yield covering earlier years of adoption, then CSIRO for later years

		significant average yield gain		adoption, then CSIRO for later years. For 2006-2009 cost of technology values confirmed by personal communication from Monsanto Australia	
Argentina	+30% all years	More conservative of the two pieces of research used	Qaim & De Janvry (2002 & 2005) analysis based on farm level analysis in 1999/00 and 2000/01 +35% yield gain, Trigo & Cap (2006) used an average gain of +30% based on work by Elena (2001)	Data derived from the same sources referred to for yield. Cost of technology all years based on industry sources	Data derived from the same sources referred to for yield and cost of technology.
South Africa	+24% all years	Lower end of estimates applied	Ismael et al (2001) identified yield gain of +24% for the years 1998/99 & 1999/2000. Kirsten et al (2002) for 2000/01 season found a range of +14% (dry crops/large farms) to +49% (small farmers) James (2002) also cited a range of impact between +27% and +48% during the years 1999-2001	Data derived from the same sources referred to for yield. Values for cost of technology and cost of insecticide cost savings also provided/confirmed from industry sources	Data derived from the same sources referred to for yield.
Mexico	+37% 1996 +3% 1997 +20% 1998 +27% 1999 +17% 2000 +9% 2001 +6.7% 2002 +6.4% 2003 +7.6% 2004 +9.25% 2005 +9% 2006 +9.28 2007 & 2008, +14.2% 2009, +10.34% 2010 and 2011, +7.2% 2012, +8.95%	Recorded yield impact data used as available for almost all years	The yield impact data for 1997 and 1998 is drawn from the findings of farm level survey work by Traxler et al (2001). For all other years the data is based on the annual crop monitoring reports submitted to the Mexican Ministry of Agriculture by Monsanto Mexico	Data derived from the same sources referred to for yield. 2009 onwards seed cost based on weighted average of single and stacked trait seed sales	Data derived from the same sources referred to for yield.

	2013, +15.8% 2014 15% 2015				
India	+45% 2002 +63% 2003 +54% 2004 +64% 2005 +50% 2006 & 2007 +40% 2008, +35% 2009 & 2010, +30% 2011, +24% 2012- 15	Recorded yield impact used for years where available	Yield impact data 2002 and 2003 is drawn from Bennett et al (2004), for 2004 the average of 2002 and 2003 was used. 2005 and 2006 are derived from IMRB (2006 & 2007). 2007 impact data based on lower end of range of impacts identified in previous 3 years (2007 being a year of similar pest pressure to 2006). 2008 onwards based on assessments of general levels of pest pressure Industry sources), Herring and Rao (2012) and Kathage, Jonas and Qaim (2012)	Data derived from the same sources referred to for yield. 2007 onwards cost of technology based on industry sources	Data derived from the same sources referred to for yield. 2007 onwards cost savings based on industry estimates and AMIS Global pesticide usage data (2011)
Brazil	+6.23% 2006 -3.6% 2007 -2.7% 2008, -3.8% 2009, 2010 nil 2011 +3.04%, 2012 -1.8%, 2013 +2.4%, 2014-2015 +2.38%	Recorded yield impacts for each year – 2013 not available so 2012 value assumed	2006 unpublished farm survey data – source: Monsanto (2008) 2007- 2010 farm survey data from Galvão (2009, 2010, 2012, 2013, 2015))	Data derived from the same sources referred to for yield	Data derived from the same sources referred to for yield
Colombia	+30% all years except 2009 +15%, 2010 onward +10%	Farm survey 2007 comparing performan ce of GM IR versus convention al growers. 2009 onwards based on trade estimates	Based on Zambrano P et al (2009) and trade estimates (2009, 2011, 2013)	Assumed as Mexico – no breakdown of seed premium provided in Zambrano (2009). From 2008 based on weighted cost of seed sold as single and stacked traits	Data derived from Zambrano P (2009). Cost savings excluding seed premium derived from Zambrano as total cost savings less assumed seed premium. 2010 onwards seed premium & cost savings from industry sources
Burkina Faso	+20 2008, +18.9%	Trials 2008, farm	Vitale J et al (2008) & Vitale J et al (2010)	Based on Vitale J et al (2008 & 2010)	Based on Vitale J et al (2008 & 2010)

	2009 onwards	survey 2009			
Pakistan	+12.6% 2009, 2010 onwards +22%	Farm surveys	Nazli H et al (2010), Kouser and Qaim (2013)	Based on data from same sources as yield impacts	Based on data from same sources as yield impacts
Myanmar	+30%	Extension service estimates	USDA (2011)	No data available so based on India and Pakistan	No data available so based on Pakistan
GM HT soybeans	Yield impact assumption used	Rationale	Yield references	Cost of technology data/assumptions	Cost savings (excluding impact of seed premium) assumptions
US: 1 st generation	Nil	Not relevant	Not relevant	Marra et al (2002) Carpenter & Gianessi (2002) Sankala & Blumenthal (2000 & 2006) Johnson S & Strom S (2008) & updated post 2008 from industry estimates of seed premia	Marra et al (2002) Carpenter & Gianessi (2002) Sankala & Blumenthal (2000 & 2006) Johnson S & Strom S (2008) & updated post 2008 to reflect herbicide price and common product usage
Canada: 1 st generation	Nil	Not relevant	Not relevant	George Morris Center (2004) & updated from 2008 based on industry estimates of seed premia	George Morris Center (2004), Ontario Ministry of Agriculture & updated for 2008 to reflect herbicide price changes
US & Canada: 2 nd generation	+5% 2009 and 2010, +10.4% 2011, +11.2% 2012, +11% 2013, +9% 2014, 8.9% 2015	Farm level monitoring and farmer feedback	Monsanto farmer surveys (annual)	Industry estimates of seed premia relative to 1 st generation GM HT seed	as 1 st generation
Argentina	Nil but second crop benefits	Not relevant except 2 nd crop – see separate table	Not relevant	Qaim & Traxler (2005), Trigo & CAP (2006) and 2006 onwards (Monsanto royalty rate)	Qaim & Traxler (2005), Trigo & CAP (2006) & updated from 2008 to reflect herbicide price changes
Brazil	Nil	Not relevant	Not relevant	As Argentina to 2002 (illegal plantings). Then based on Parana Department of Agriculture	Sources as in cost of technology

				(2004). Also agreed royalty rates from 2004 applied to all years to 2006. 2007 onwards based on Galvão (2009, 2010, 2012, 2013 and 2015)	
Paraguay	Nil but second crop benefits	Not relevant except 2 nd crop	Not relevant	As Argentina: no country-specific analysis identified. Impacts confirmed from industry sources (annual personal communications 2006-2012). Seed cost based on royalty rate since 2007	As Argentina – herbicide cost differences adjusted post 2008 based on industry sources and AMIS Global herbicide usage data 2011, 2013, 2015
South Africa	Nil	Not relevant	Not relevant	No studies identified. Seed premia based on industry sources (annually updated)	No studies identified. Based on industry estimates (annually updated) and AMIS Global herbicide usage data 2011, 2013, 2015
Uruguay	Nil	Not relevant	Not relevant	As Argentina: no country-specific analysis identified. Seed premia based on industry sources	As Argentina: no country-specific analysis identified. Impacts based on industry sources and AMIS Global herbicide usage data 2011, 2013, 2015
Mexico	+9.1% 2004 & 2005 +3.64% 2006 +3.2% 2007 +2.4% 2008 +13% 2009, +4% 2010-2-12, +9.9% 2013, -2.1% 2014, -0.75% 2015	Recorded yield impact from studies	From Monsanto annual monitoring reports submitted to Ministry of Agriculture	No published studies identified based on Monsanto annual monitoring reports	No published studies identified based on Monsanto annual monitoring reports
Romania	+31%, 15% 2006	Based on only available study covering	For previous year – based on Brookes (2005) – the only published source identified. Also,	Brookes (2005) Monsanto Romania (2007)	Brookes (2005) Monsanto Romania (2007)

		1999-2003 (note not grown in 2007) plus 2006 farm survey	Monsanto Romania (2007)		
Bolivia	+15%	Based on survey in 2007-08	Fernandez W et al (2009) farm survey	Fernandez W et al (2009)	Fernandez W et al (2009)
GM HT & IR soybeans					
Brazil	+9.6% 2013, +9.1% 2014, 9.4% 2015	Farm trials and post market monitoring survey	Monsanto farm trials and commercial crop monitoring (survey)	As yield source	As yield source
Argentina	+9.1% 2013, +7.8% 2014, 7.1% 2015	As Brazil	Monsanto farm trials and commercial crop monitoring (survey)	As yield source	As yield source
Paraguay	+12.8% 2013, +11.9% 2014, 9.1% 2015	As Brazil	Monsanto farm trials and commercial crop monitoring (survey)	As yield source	As yield source
Uruguay	+8.8% 2013, +7.8% 2014, 7% 2015	As Brazil	Monsanto farm trials and commercial crop monitoring (survey)	As yield source	As yield source
GM HT corn	Yield impact assumption used	Rationale	Yield references	Cost of technology data/assumptions	Cost savings (excluding impact of seed premium) assumptions
US	Nil	Not relevant	Not relevant	Carpenter & Gianessi (2002) Sankala & Blumenthal (2003 & 2006) Johnson S & Strom S (2008). 2008 and 2009 onwards based on weighted seed sales (sold as single and stacked traits)	Carpenter & Gianessi (2002) Sankala & Blumenthal (2003 & 2006) Johnson S & Strom S (2008). 2009 onwards updated to reflect changes in common herbicide treatments and prices
Canada	Nil	Not relevant	Not relevant	No studies identified – based on annual personal communications with industry sources	No studies identified – based on industry and extension service estimates of herbicide regimes and updated since 2008 on the basis of

					changes in herbicide price changes
Argentina: sold as single trait	+3% corn belt +22% marginal areas	Based on only available analysis - Corn Belt = 70% of plantings, marginal areas 30% - industry analysis (note no significant plantings until 2006)	No studies identified – based on personal communications with industry sources in 2007 and 2008 Monsanto Argentina & Grupo CEO (personal communications 2007, 2008 & 2011)	Industry estimates of seed premia and weighted by seed sales according to whether containing single or stacked traits	No studies identified - based on Monsanto Argentina & Grupo CEO (personal communications 2007 & 2008). 2008 & 2009 updated to reflect herbicide price changes
Argentina: sold as stacked trait	+10.25%	Farmer level feedback to seed suppliers	Unpublished farm level survey feedback to Monsanto: +15.75% yield impact overall – for purposes of this analysis, 5.5% allocated to IR trait and balance to HT trait	As single trait	As single trait
South Africa	Nil	Not relevant	Not relevant	Industry sources – annual checked	No studies identified - based on Monsanto S Africa (personal communications 2005, 2007 & 2008). 2008 onwards updated to reflect herbicide price changes
Philippines	+15% 2006 and 2007, +5% 2008 onwards	Farm survey	Based on unpublished industry analysis for 2006 & 2007, thereafter Gonsales L et al (2009)	Monsanto Philippines (personal communications 2007 & 2008). Gonsales L et al (2009). 2010 updated to reflect changes in seed costs	Monsanto Philippines (personal communications 2007 & 2008). Gonsales L et al (2009). 2010 onwards updated annually to reflect changes in herbicide costs
Brazil	+2.5% 2010 +3.6% 2011. +6.84% 2012 and 2013, +3% 2014-2015	Farm survey	Galvão (2010, 2012, 2013, 2015))	Data derived from the same sources referred to for yield	Data derived from the same sources referred to for yield plus AMIS Global herbicide use data
Colombia	Zero	Mendez et al (2011)	Mendez et al (2011) farm survey from 2009	Mendez et al (2011)	Mendez et al (2011)

Uruguay	Zero	Not relevant	Not relevant	No studies available – based on Argentina	No studies available – based on Argentina plus annual AMIS Global herbicide use data
Paraguay	Zero	Not relevant	Not relevant	No studies available – based on Argentina	No studies available – based on Argentina plus annual AMIS Global herbicide use data
GM HT Cotton	Yield impact assumption used	Rationale	Yield references	Cost of technology data/assumptions	Cost savings (excluding impact of seed premium) assumptions
US	Nil	Not relevant	Not relevant	Carpenter & Gianessi) Sankala & Blumenthal (2003 & 2006) Johnson S & Strom S (2008) and updated from 2008 based on weighted seed sales (by single and stacked trait seed)	Carpenter & Gianessi) Sankala & Blumenthal (2003 & 2006) Johnson S & Strom S (2008) and updated from 2008 to reflect changes in weed control practices and prices of herbicides
Australia	Nil	Not relevant	Not relevant	Doyle et al (2003) Monsanto Australia (personal communications 2005, 2007, 2009, 2010 and 2012)	Doyle et al (2003) Monsanto Australia (personal communications 2005, 2007, 2009, 2010, 2012), 2016
South Africa	Nil	Not relevant	Not relevant	No studies identified - based on Monsanto S Africa (personal communications 2005, 2007, 2008, 2010 and 2012)	No studies identified - based on Monsanto S Africa (personal communications 2005, 2007, 2008, 2010, 2012, 2016)
Argentina	Nil on area using farm saved seed, +9.3% on area using certified seed	Based on only available data – company monitoring of commercial plots	No studies identified – based on personal communications with Grupo CEO and Monsanto Argentina (2007, 2008, 2012)	No published studies identified – based on personal communications with Grupo CEO and Monsanto Argentina (2007, 2008 & 2010 and 2012)	No published studies identified – based on personal communications with Grupo CEO and Monsanto Argentina (2007, 2008 & 2010, 2012, 2013, 2016)
Mexico	+3.6% all years to 2007	Based on annual monitoring	Same as source for cost data	No published studies identified - based on	No published studies identified - based on annual personal

	0% 2008, +5.11% 2009, +18.1% 2010, +5.1% 2011, +13.1% 2012, +14.2% 2013, +13.3% 2014, +19.6% 2015	reports to Ministry of Agriculture by Monsanto Mexico		personal communications with Monsanto Mexico and their annual reporting	communications with Monsanto Mexico and their annual reporting
Colombia	+4%	Based on only available data – company monitoring of commercial plots	As cost data	No published studies identified – based on personal communications with Monsanto Colombia (2010, 2012, 2013)	No published studies identified – based on personal communications with Monsanto Colombia (2010, 2012, 2013)
Brazil	+2.35% 2010 +3.1% 2011, -1.8% 2012, +1.6% 2013, +1.6% 2014-15	Farm survey	Galvão (2010, 2012, 2013, 2015)	Data derived from the same sources referred to for yield	Data derived from the same sources referred to for yield
GM HT canola	Yield impact assumption used	Rationale	Yield references	Cost of technology data/assumptions	Cost savings (excluding impact of seed premium) assumptions
US	+6% all years to 2004. Post 2004 based on Canada – see below	Based on the only identified impact analysis – post 2004 based on Canadian impacts as same alternative (conventional HT) technology to Canada available	Same as for cost data	Sankala & Blumenthal (2003 & 2006)) Johnson S & Strom S (2008). These are the only studies identified that examine GM HT canola in the US. Updated based on industry and extension service estimates	Sankala & Blumenthal (2003 & 2006)) Johnson S & Strom S (2008). These are the only studies identified that examine GM HT canola in the US. Updated since 2008 based on changes in herbicide prices
Canada	+10.7% all years to 2004. Post	After 2004 based on differences	Same as for cost data	Based on Canola Council (2001) to 2003 then	Based on Canola Council (2001) to 2003 then adjusted to reflect main

	<p>2004; for GM glyphosate tolerant varieties no yield difference 2004, 2005, 2008, 2010 +4% 2006 and 2007, +1.67% 2009, +1.6% 2011, +1.5% 2012, +3.1% 2013, +3.4% 2014, +4.3% 2015 For GM glufosinate tolerant varieties: +12% 2004, +19% 2005, +10% 2006 & 2007 +12% 2008 +11.8% 2009, +10.9% 2010, +4.6% 2011, +4.8% 2012, +10.1% 2013, +11% 2014, +11.6% 2015</p>	<p>between average annual variety trial results for Clearfields (non GM herbicide tolerant varieties) and GM alternative s. GM alternative s differentiated into glyphosate tolerant and glufosinate tolerant</p>		<p>adjusted to reflect main current non GM (HT) alternative of 'Clearfields' – data derived from personal communications with the Canola Council (2008) plus Gusta M et al (2009)</p>	<p>current non GM (HT) alternative of 'Clearfields' – data derived from personal communications with the Canola Council (2008) plus Gusta M et al (2009) which includes spillover benefits of \$ Can13.49 to follow on crops – applied from 2006. Also adjusted annually to reflect changes in typical herbicides used on different crops (GM HT, conventional, Clearfields)</p>
Australia	<p>+21.08% 2008, +20.9% 2009, +15.8% 2010, +7.6% 2011 and 2012, +11% 2013-2015</p>	<p>Survey based with average yield gain based on weighting yield gains for different types of seed by seed sales or number of farmers using</p>	<p>Based on survey of licence holders by Monsanto Australia, Fischer and Tozer (2009) and Hudson (2013)</p>	<p>Sources as for yield changes</p>	<p>Sources as for yield changes</p>

		different seed types			
GM HT sugar beet					
US & Canada	+12.58% 2007 +2.8% 2008 +3.3% 2009-2012, +3.1% 2013, +3.2% 2014, +3.55% 2015	Farm survey & extension service analysis	Kniss (2008) Khan (2008)	Kniss A (2008) Khan M (2008),	Kniss A (2010) Khan M (2008), Jon-Joseph A and Sprague C (2010) and updated annually to reflect changes in herbicide usage and prices
GM VR crops US					
Papaya	between +15% and +77% 1999-2012 – relative to base yield of 22.86 t/ha	Based on average yield in 3 years before first use	Draws on only published source disaggregating to this aspect of impact	Sankala & Blumenthal (2003 & 2006), Johnson S & Strom S (2008)	Nil – no effective conventional method of protection
Squash	+100% on area planted	assumes virus otherwise destroys crop on planted area	Draws on only published source disaggregating to this aspect of impact	Sankala & Blumenthal (2003 & 2006), Johnson S & Strom S (2008)	Sankala & Blumenthal (2003 & 2006), Johnson S & Strom S (2008) and updating of these from 2008

Readers should note that the assumptions are drawn from the references cited supplemented and updated by industry sources (where the authors have not been able to identify specific studies). This has been particularly of relevance for some of the herbicide tolerant traits more recently adopted in several developing countries. Accordingly, the authors are grateful to industry sources which have provided information on impact, (notably on cost of the technology and impact on costs of crop protection). Whilst this information does not derive from detailed studies, the authors are confident that it is reasonably representative of average impacts; in a number of cases, information provided from industry sources via personal communications has suggested levels of average impact that are lower than that identified in independent studies. Where this has occurred, the more conservative (industry source) data has been used.

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 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 1996-2015 (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 \$)
1996	0.45	128.78	Negligible
1997	0.65	127.20	25.4
1998	0.8	125.24	43.8
1999	1.4	122.76	116.6
2000	1.6	125.38	144.2
2001	2.4	124.00	272.8
2002	2.7	143.32	372.6
2003	2.8	151.33	416.1
2004	3.0	226.04	678.1
2005	2.3	228.99	526.7
2006	3.2	218.40	698.9
2007	4.94	229.36	1,133.6
2008	3.35	224.87	754.1
2009	3.55	207.24	736.0
2010	4.40	257.70	1,133.8
2011	4.60	257.40	1,184.0
2012	2.90	291.00	844.6
2013	3.46	289.80	1,001.6
2014	4.00	195.91	783.6
2015	3.76	128.51	483.8

Source & notes:

1. Crop areas and gross margin data based on data supplied by Grupo CEO and the Argentine Ministry of Agriculture. No data available before 2000, hence 2001 data applied to earlier years but adjusted, based on GDP deflator rates
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 (less an assumed area of second crop soybeans that equals the second crop area in 1996 – this was discontinued from 2004 because of the importance farmers attach to the GM HT system in facilitating them remaining in no tillage production systems)

Appendix 3: Additional information relating to the environmental impact: example comparisons

US Soybeans: typical herbicide regimes for conventional no tillage production systems: Mid West

	Active ingredient (kg/ha)	Field EIQ/ha value
<i>Option 1</i>		
Glyphosate	1.16	17.78
2 4 D	0.64	9.79
Flumioxazin	0.08	1.89
Chlorimuron	0.02	0.43
Lactofen	0.19	2.90
Clethodim	0.19	3.24
Total	2.28	36.02
<i>Option 2</i>		
Glyphosate	1.16	17.78
2 4 D	0.64	9.79
Flumioxazin	0.07	1.74
Chlorimuron	0.02	0.43
Thifensulfuron	0.01	0.11
Fomesafen	0.24	5.76
Clethodim	0.19	3.24
Total	2.33	38.84
<i>Option 3</i>		
Glyphosate	1.17	17.78
2 4 D	0.64	9.79
Sulfentrazone	0.20	2.39
Cloransulam	0.03	0.39
Clethodim	0.19	3.24
Total	2.24	33.89

US Soybeans: typical herbicide regimes for conventional no tillage production systems: South

	Active ingredient (kg/ha)	Field EIQ/ha value
<i>Option 1</i>		
Glyphosate	1.16	17.78
2 4 D	0.64	9.79
Flumioxazin	0.07	1.78
Metolochlor	1.36	29.97
Fomesafen	0.30	7.32
Clethodim	0.19	3.24
Total	3.72	69.82
<i>Option 2</i>		
Glyphosate	1.16	17.78
2 4 D	0.64	9.79
Flumioxazin	0.07	1.78
Chlorimuron	0.02	0.4
Fomesafen	0.37	9.03
Clethodim	0.19	3.24
Total	2.45	42.03
<i>Option 3</i>		

Glyphosate	1.16	17.78
2 4 D	0.64	9.79
Metalochlor	1.36	29.97
Fomesafen	0.30	7.32
Acifloren	0.32	7.48
S Metalochlor	1.45	31.88
Clethodim	0.19	3.24
Total	5.42	107.45

**US Soybeans: typical herbicide regimes for conventional crop and tillage production systems:
South**

	Active ingredient (kg/ha)	Field EIQ/ha value
<i>Option 1</i>		
Flumioxazin	0.07	1.72
Metalochlor	1.38	30.39
Fomesafen	0.30	7.42
Clethodim	0.19	3.24
Total	1.95	42.77
<i>Option 2</i>		
Flumioxazin	0.08	1.89
Chlorimuron	0.02	0.43
Fomesafen	0.24	5.76
Clethodim	0.19	3.24
Total	0.53	11.32
<i>Option 3</i>		
Metalochlor	1.36	29.97
Fomesafen	0.30	7.32
Acifloren	0.32	7.48
S Metalochlor	1.45	31.88
Clethodim	0.19	7.48
Total	3.62	79.88

Weighted average all by tillage types: ai/ha 2.40 kg/ha, EIQ/ha 47.52

Estimated typical herbicide regimes for GM HT reduced/no till and conventional reduced/no till soybean production systems that will provide an equal level of weed control to the GM HT system in Argentina 2015

	Active ingredient (kg/ha)	Field EIQ/ha value
<i>GM HT soybean</i>	3.59	55.84
Source: AMIS Global dataset on pesticide use 2015		
<i>Conventional soybean</i>		
<i>Option 1</i>		
Glyphosate	1.92	29.43
Metsulfuron	0.03	0.50
2 4 D	0.4	8.28
Imazethapyr	0.10	1.96
Diflufenican	0.03	0.29
Clethodim	0.19	3.23
Total	2.67	43.70
<i>Option 2</i>		
Glyphosate	1.92	29.43
Dicamba	0.12	3.04
Acetochlor	1.35	26.87
Haloxifop	0.18	4.00
Sulfentrazone	0.19	2.23
Total	3.76	65.55
<i>Option 3</i>		
Glyphosate	1.92	29.43
Atrazine	1.07	24.50
Bentazon	0.60	11.22
2 4 D ester	0.4	6.12
Imazaquin	0.024	0.37
Total	4.01	71.64
<i>Option 4</i>		
Glyphosate	1.92	29.43
2 4 D amine	0.4	8.28
Flumetsulam	0.06	0.94
Fomesafen	0.25	6.13
Chlorimuron	0.05	0.96
Fluazifop	0.12	3.44
Total	2.80	49.18
<i>Option 5</i>		
Glyphosate	1.92	29.43
Metsulfuron	0.03	0.50
2 4 D amine	0.8	16.56
Imazethapyr	0.1	1.96
Haloxifop	0.18	4.00
Total	3.03	52.45
<i>Option 6</i>		
Glyphosate	1.92	29.43
Metsulfuron	0.03	0.50
2 4 D amine	0.8	16.56
Imazethapyr	0.1	1.96

Clethodim	0.24	4.08
Total	3.09	52.53
Average all six conventional options	3.23	55.84

Sources: AAPRESID, AMIS Global, Monsanto Argentina

GM HT versus conventional maize Argentina 2015

	Active ingredient (kg/ha)	Field EIQ/ha value
Conventional		
<i>Option 1</i>		
Acetochlor	1.26	25.07
Atrazine	1.80	41.22
Idosulfuron	0.01	0.16
Nicosulfuron	0.09	1.76
2 4 D	0.38	5.83
Total	3.54	74.04
<i>Option 2</i>		
Acetochlor	1.26	25.07
Atrazine	1.80	41.22
Foramsulam	0.06	0.92
Idosulfuron	0.01	0.16
2 4 D	0.38	5.83
Total	3.51	73.2
Average conventional	3.53	93.61
GM HT corn		
Acetochlor	0.84	16.72
Atrazine	0.9	20.61
Glyphosate	1.87	28.65
2 4 D	0.38	5.83
Total	3.99	71.81

Sources: AMIS Global and Monsanto Argentina

Typical herbicide regimes for GM HT soybeans Brazil 2015

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
<i>Burndown (applicable to conventional and GM HT)</i>	1.78	30.07
<i>GM HT over the top</i>	0.81	10.56
GM HT total	2.59	40.63
<i>Conventional over the top</i>	0.75	17.33
Conventional total	2.53	47.40

Source: derived from Kleffmann & AMIS Global

Typical herbicide regimes for GM HT soybean in South Africa 2015

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
<i>Conventional soybean</i>		
<i>Option one</i>		
Alachlor	1.87	33.47
Chlorimuron	0.01	0.19
Total	1.88	33.66
<i>Option two</i>		

S Metolachlor	0.92	20.13
Dimethenamid	0.5	6.06
Total	1.42	26.19
<i>Option 3</i>		
S Metolachlor	0.92	20.13
Chlorimuron	0.01	0.19
Total	0.93	20.32
Weighted average	1.46	27.11
<i>GM HT soybean – based on AMIS Global 2014</i>	1.08	16.56

Source: Monsanto South Africa, AMIS Global

Note conventional average weighted by active ingredient use in AMIS Global – option 1 70%, option 2 20%, option 3 10%

Typical herbicide regimes for GM HT cotton in South Africa 2015

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
<i>Conventional cotton</i>		
<i>Option one</i>		
Trifluralin	1.12	21.06
Total	1.12	21.06
<i>Option two</i>		
S Metolachlor	0.96	20.9
Flumeturon	0.4	5.72
Prometryn	0.5	7.70
Total	1.85	34.48
<i>Option 3</i>		
Trifluralin	1.12	21.06
Cyanazine	0.85	11.56
Total	1.97	32.62
<i>Option 4</i>		
Trifluralin	1.12	21.06
Flumeturon	0.4	5.72
Prometryn	0.5	7.70
Acetochlor	0.32	6.37
Atrazine	0.128	2.93
Total	2.093	43.77
<i>Option 5</i>		
Trifluralin	0.75	14.10
Flumeturon	0.4	5.72
Prometryn	0.5	7.70
Total	1.65	27.52
Average conventional	1.81	31.86
<i>GM HT cotton</i>		
Glyphosate	1.8	27.59

Source: Monsanto South Africa

Typical herbicide regimes for GM HT maize in Canada 2015

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
<i>Conventional maize</i>		
Metolachlor	1.36	29.84
Atrazine	1.19	27.28

Primsulfuron	0.024	0.41
Dicamba	0.14	3.54
Total	2.71	61.07
<i>GM glyphosate tolerant maize</i>		
Metalochlor	0.68	14.92
Atrazine	0.59	13.60
Glyphosate	0.56	8.58
Total	1.83	37.10
<i>GM glufosinate tolerant maize</i>		
Metalochlor	0.68	14.92
Atrazine	0.59	13.60
Glufosinate	0.37	7.49
Total	1.64	36.01

Sources: Weed Control Guide Ontario – annually updated, industry personal communications (various)

Typical insecticide regimes for cotton in India 2015

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
<i>Conventional cotton</i>		
<i>Option 1</i>		
Imidacloprid	0.06	2.2
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.45
Diafenthiuron	0.1	2.53
Buprofezin	0.07	2.55
Profenfos	0.81	48.28
Acephate	0.63	15.79
Cypermethrin	0.1	3.64
Metaflumizone	0.03	0.82
Novaluron	0.04	0.57
Total	1.94	79.5
<i>Option 2</i>		
Imidacloprid	0.06	2.2
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.45
Diafenthiuron	0.1	2.53
Chlorpyrifos	0.39	10.58
Profenfos	0.81	48.28
Metaflumizone	0.03	0.82
Emamectin	0.01	0.29
Total	1.50	67.83
Average conventional	1.73	73.67
<i>GM IR cotton</i>		
Imidacloprid	0.06	2.2
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.45
Diafenthiuron	0.1	2.53
Buprofezin	0.07	2.55
Acephate	0.63	15.79
Total	0.97	26.19
<i>Option 2</i>		

Imidacloprid	0.06	1.54
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	2.30
Diafenthiuron	0.1	2.53
Total	0.26	8.04
Weighted average GM IR cotton	0.68	18.85

Source: Monsanto India, AMIS Global

Note weighted average for GM IR cotton based on insecticide usage – option 1 60%, option 2 40%

Typical insecticide regimes for cotton in China 2015

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
<i>Conventional cotton</i>		
Imidacloprid	0.162	5.95
Abamectin	0.032	1.11
Chlorpyrifos	0.64	17.18
Deltamethrin	0.068	1.93
Phoxim	0.99	24.75
Methomyl	0.249	5.48
Profenphos	0.84	50.0
Total	2.981	106.40
<i>GM IR cotton</i>		
Imidacloprid	0.108	3.96
Abamectin	0.032	1.11
Chlorpyrifos	0.448	12.03
Deltamethrin	0.034	0.96
Phoxim	0	0
Methomyl	0.249	5.48
Profenphos	0.84	50.0
Total	1.711	73.54

Sources: Monsanto China, AMIS Global, Plant Protection Institute of the Chinese Academy of Agricultural Sciences

Typical herbicide regimes for GM HT cotton Australia 2015

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
<i>Conventional cotton</i>		
<i>Option 1 'dirty'</i>		
Trifluralin	1.2	22.60
Diuron	0.925	24.48
Glyphosate	0.9	13.80
Prometryn	0.66	10.14
Flumeturon	0.44	6.28
Diuron	1.85	48.97
Metalochlor	1.44	31.68
Clethodim	0.12	2.04
Prometryn	1.25	19.21
Total	8.78	179.20
<i>Option 2 'moderate'</i>		
Trifluralin	1.2	22.60
Glyphosate	0.45	6.90
Flumeturon	0.66	9.42
Flumeteron	0.4	5.71

Prometryn	1	15.37
Prometryn	1.5	23.06
Clethodim	0.12	2.04
Metalochlor	1.44	31.68
Total	6.77	116.77
<i>Option 3 'clean'</i>		
Diuron	1.0	26.47
Glyphosate	0.45	6.90
Flumeteron	0.44	6.28
Prometryn	0.66	10.14
Paraquat	0.25	6.18
Diquat	0.2	4.95
Pyrithiobic sodium	0.006	0.13
Prometryn	0.66	10.14
Total	3.666	71.19
<i>GM HT cotton</i>		
<i>Option 1 'dirty'</i>		
Trifluralin	0.864	16.27
Diuron	0.46	12.18
Prometryn	0.66	10.14
Flumeteron	0.44	6.28
Glyphosate over the top	3.105	47.60
Glyphosate burn down	0.48	7.36
Total	6.009	99.83
<i>Option 2 'moderate'</i>		
Pendimethalin	0.99	29.87
Flumeteron	0.44	6.28
Glyphosate over the top	3.11	47.60
Glyphosate burn down	0.48	7.36
Total	5.02	91.11
<i>Option 3 'clean'</i>		
Glyphosate over the top	2.07	31.73
Glyphosate burn down	0.45	6.90
Total	2.52	38.63

Source: Monsanto Australia

Typical insecticide regimes for cotton in Mexico 2015

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
<i>Conventional cotton</i>		
Lambda cyhalothrin	0.04	1.89
Cypermethrin	0.16	5.82
Monocrotophos	0.6	22.08
Methidathion	0.622	20.34
Triazophos	0.6	21.36
Methomyl	0.225	4.95
Chlorpyrifos	0.96	25.82
Chlorfenapyr	0.12	5.53
Endosulfan	1.08	41.69
Azinphos methyl	0.315	14.52
Parathion methyl	0.5	13.0
Total	5.222	177.00
<i>GM IR cotton</i>		

Lambda cyhalothrin	0.02	0.94
Cypermethrin	0.08	2.91
Monocrotophos	0.3	11.04
Methomyl	0.225	4.95
Chlorpyrifos	0.96	25.82
Chlorfenapyr	0.12	5.53
Endosulfan	1.08	41.69
Azinphos methyl	0.315	14.52
Parathion methyl	0.5	13.0
Total	3.60	120.41

Typical conventional insecticide regime for maize (targeting corn boring pests) in Colombia 2015

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
Luferon	0.0225	0.37
Chlorifluzanon	0.05	1.82
Chlorpyrifos	0.325	8.73
Mathavin	0.162	4.97
Total	0.561	15.89

Source: Mendez et al (2011)

Note: GM IR maize replaces the above treatment

Appendix 4: The Environmental Impact Quotient (EIQ): a method to measure the environmental impact of pesticides

The material presented below is from the original by the cited authors of J. Kovach, C. Petzoldt, J. Degni, and J. Tette, IPM Program, Cornell University,

Methods

Extensive data are available on the environmental effects of specific pesticides, and the data used were gathered from a variety of sources. The Extension Toxicology Network (EXTOXNET), a collaborative education project of the environmental toxicology and pesticide education departments of Cornell University, Michigan State University, Oregon State University, and the University of California, was the primary source used in developing the database (Hotchkiss et al. 1989). EXTOXNET conveys pesticide-related information on the health and environmental effects of approximately 100 pesticides. A second source of information used was CHEM-NEWS of CENET, the Cornell Cooperative Extension Network. CHEM-NEWS is a computer program maintained by the Pesticide Management and Education Program of Cornell University that contains approximately 310 US EPA - Pesticide Fact Sheets, describing health, ecological, and environmental effects of the pesticides that are required for the re-registration of these pesticides (Smith and Barnard 1992).

The impact of pesticides on arthropod natural enemies was determined by using the SELCTV database developed at Oregon State (Theiling and Croft 1988). These authors searched the literature and rated the effect of about 400 agrichemical pesticides on over 600 species of arthropod natural enemies, translating all pesticide/natural enemy response data to a scale ranging from one (0% effect) to five (90-100% effect).

Leaching, surface loss potentials (runoff), and soil half-life data of approximately 100 compounds are contained in the National Pesticide/Soils Database developed by the USDA Agricultural Research Service and Soil Conservation Service. This database was developed from the GLEAMS computer model that simulates leaching and surface loss potential for a large number of pesticides in various soils and uses statistical methods to evaluate the interactions between pesticide properties (solubility, absorption coefficient, and half-life) and soil properties (surface horizon thickness, organic matter content, etc.). The variables that provided the best estimate of surface loss and leaching were then selected by this model and used to classify all pesticides into risk groups (large, medium, and small) according to their potential for leaching or surface loss.

Bee toxicity was determined using tables by Morse (1989) in the 1989 New York State pesticide recommendations, which contain information on the relative toxicity of pesticides to honey bees from laboratory and field tests conducted at the University of California, Riverside from 1950 to 1980. More than 260 pesticides are listed in this reference.

In order to fill as many data gaps as possible, Material Safety Data Sheets (MSDS) and technical bulletins developed by the agricultural chemical industry were also used when available.

Health and environmental factors that addressed some of the common concerns expressed by farm workers, consumers, pest management practitioners, and other environmentalists were

evaluated and are listed in Figure 1. To simplify the interpretation of the data, the toxicity of the active ingredient of each pesticide and the effect on each environmental factor evaluated were grouped into low, medium, or high toxicity categories and rated on a scale from one to five, with one having a minimal impact on the environment or of a low toxicity and five considered to be highly toxic or having a major negative effect on the environment.

All pesticides were evaluated using the same criteria except for the mode of action and plant surface persistence of herbicides. As herbicides are generally systemic in nature and are not normally applied to food crops we decided to consider this class of compounds differently, so all herbicides were given a value of one for systemic activity. This has no effect on the relative rankings within herbicides, but it does make the consumer component of the equation for herbicides more realistic. Also, since plant surface persistence is only important for post-emergent herbicides and not pre-emergent herbicides, all post-emergent herbicides were assigned a value of three and pre-emergent herbicides assigned a value of one for this factor.

The rating system used to develop the environmental impact quotient of pesticides (EIQ) model is as follows (1 = least toxic or least harmful, 5 = most toxic or harmful):

- *Mode of Action*: non-systemic- 1, all herbicides – 1, systemic – 3
- *Acute Dermal LD50 for Rabbits/Rats(m&/kg)*: >2000 – 1, 200 - 2000 – 3, 0 - 200 – 5
- *Long-Term Health Effects*: little or none – 1, possible- 3, definite – 5
- *Plant Surface Residue Half-life*: 1-2 weeks- 1, 2-4 weeks- 3, > 4 weeks – 5, pre-emergent herbicides – 1, post-emergent herbicides – 3
- *Soil Residue Half-life*: T1/2 <30 days – 1, T1/2=30-100 days – 3, T1/2 >100 days – 5
- *Toxicity to Fish-96 hr LC50*: > 10 ppm – 1, 1-10 ppm – 3, < 1 ppm – 5
- *Toxicity to Birds-8 day LC50*: > 1000 ppm – 1, 100-1000 ppm – 3, 1-100 ppm – 5
- *Toxicity to Bees*: relatively non toxic – 1, moderately toxic – 3, highly toxic – 5
- *Toxicity to Beneficials*: low impact- 1, moderate impact – 3, severe impact – 5
- *Groundwater and Runoff Potential*: small – 1, medium – 3, large -5

In order to further organise and simplify the data, a model was developed called the environmental impact quotient of pesticides (EIQ). This model reduces the environmental impact information to a single value. To accomplish this, an equation was developed based on the three principal components of agricultural production systems: a farm worker component, a consumer component, and an ecological component. Each component in the equation is given equal weight in the final analysis, but within each component, individual factors are weighted differently. Coefficients used in the equation to give additional weight to individual factors are also based on a one to five scale. Factors carrying the most weight are multiplied by five, medium-impact factors are multiplied by three, and those factors considered to have the least impact are multiplied by one. A consistent rule throughout the model is that the impact potential of a specific pesticide on an individual environmental factor is equal to the toxicity of the chemical times the potential for exposure. Stated simply, environmental impact is equal to toxicity times exposure. For example, fish toxicity is calculated by determining the inherent toxicity of the compound to fish times the likelihood of the fish encountering the pesticide. In this manner, compounds that are toxic to fish but short-lived have lower impact values than compounds that are toxic and long-lived.

The EIQ Equation

The formula for determining the EIQ value of individual pesticides is listed below and is the average of the farm worker, consumer, and ecological components:

$$EIQ = [C[(DT*5)+(DT*P)] + [(C*((S+P)/2)*SY) + (L)] + [(F*R) + (D*((S+P)/2)*3) + (Z*P*3) + (B*P*5)]] / 3$$

DT = dermal toxicity, C = chronic toxicity, SY = systemicity, F = fish toxicity, L = leaching potential, R = surface loss potential, D = bird toxicity, S = soil half-life, Z = bee toxicity, B = beneficial arthropod toxicity, P = plant surface half-life.

Farm worker risk is defined as the sum of applicator exposure (DT* 5) plus picker exposure (DT*P) times the long-term health effect or chronic toxicity (C). Chronic toxicity of a specific pesticide is calculated as the average of the ratings from various long-term laboratory tests conducted on small mammals. These tests are designed to determine potential reproductive effects (ability to produce offspring), teratogenic effects (deformities in unborn offspring), mutagenic effects (permanent changes in hereditary material such as genes and chromosomes), and oncogenic effects (tumour growth). Within the farm worker component, applicator exposure is determined by multiplying the dermal toxicity (DT) rating to small laboratory mammals (rabbits or rats) times a coefficient of five to account for the increased risk associated with handling concentrated pesticides. Picker exposure is equal to dermal toxicity (DT) times the rating for plant surface residue half-life potential (the time required for one-half of the chemical to break down). This residue factor takes into account the weathering of pesticides that occurs in agricultural systems and the days to harvest restrictions that may be placed on certain pesticides. The consumer component is the sum of consumer exposure potential ($C*((S+P)/2)*SY$) plus the potential groundwater effects (L). Groundwater effects are placed in the consumer component because they are more of a human health issue (drinking well contamination) than a wildlife issue. Consumer exposure is calculated as chronic toxicity (C) times the average for residue potential in soil and plant surfaces (because roots and other plant parts are eaten) times the systemic potential rating of the pesticide (the pesticide's ability to be absorbed by plants). The ecological component of the model is composed of aquatic and terrestrial effects and is the sum of the effects of the chemicals on fish ($F*R$), birds ($D*((S+P)/2)*3$), bees ($Z*P*3$), and beneficial arthropods ($B*P*5$). The environmental impact of pesticides on aquatic systems is determined by multiplying the chemical toxicity to fish rating times the surface runoff potential of the specific pesticide (the runoff potential takes into account the half-life of the chemical in surface water).

The impact of pesticides on terrestrial systems is determined by summing the toxicities of the chemicals to birds, bees, and beneficial arthropods. As terrestrial organisms are more likely to occur in commercial agricultural settings than fish, more weight is given to the pesticidal effects on these terrestrial organisms. Impact on birds is measured by multiplying the rating of toxicity to birds by the average half-life on plant and soil surfaces times three. Impact on bees is measured by taking the pesticide toxicity ratings to bees times the half-life on plant surfaces times three. The effect on beneficial arthropods is determined by taking the pesticide toxicity rating to beneficial natural enemies, times the half-life on plant surfaces times five. As arthropod natural enemies spend almost all of their life in agro ecosystem communities (while birds and bees are somewhat transient), their exposure to the pesticides, in theory, is greater. To adjust for this increased exposure, the pesticide impact on beneficial arthropods is multiplied by five. Mammalian wildlife toxicity is not included in the terrestrial component of the equation because mammalian exposure (farm worker and consumer) is already included in the equation, and these

health effects are the results of tests conducted on small mammals such as rats, mice, rabbits, and dogs.

After the data on individual factors were collected, pesticides were grouped by classes (fungicides, insecticides/miticides, and herbicides), and calculations were conducted for each pesticide. When toxicological data were missing, the average for each environmental factor within a class was determined, and this average value was substituted for the missing values. Thus, missing data did not affect the relative ranking of a pesticide within a class. The values of individual effects of each pesticide (applicator, picker, consumer, groundwater, aquatic, bird, bee, beneficials), the major components of the equation (farm worker, consumer, and ecological) and the average EIQ values are presented in separate tables (see references).

EIQ field use rating

Once an EIQ value has been established for the active ingredient of each pesticide, field use calculations can begin. To accurately compare pesticides and pest management strategies, the dose, the formulation or percent active ingredient of the product, and the frequency of application of each pesticide, need to be determined. To account for different formulations of the same active ingredient and different use patterns, a simple equation called the EIQ field use rating was developed. This rating is calculated by multiplying the EIQ value for the specific chemical obtained in the tables by the percent active ingredient in the formulation by the rate per acre used (usually in pints or pounds of formulated product);

$$\text{EIQ Field Use Rating} = \text{EIQ} \times \% \text{ active ingredient} \times \text{Rate}$$

By applying the EIQ Field Use Rating, comparisons can be made between different pest management strategies or programs. To compare different pest management programs, EIQ Field Use Ratings and number of applications throughout the season are determined for each pesticide and these values are then summed to determine the total seasonal environmental impact of the particular strategy.

Appendix 5 Soil carbon sequestration key literature

Soil organic carbon can be depleted through:

- the long-term use of farming practices; and
- the conversion of natural ecosystems (such as forest lands, prairie lands and steppes) into crop and grazing land.

These uses deplete the soil organic carbon pool by increasing the rate of conversion of soil organic matter to carbon dioxide, thereby reducing the input of biomass carbon and accentuating losses by erosion. Most agricultural soils have lost 30 tonnes/ha to 40 tonnes/ha of carbon, and their current reserves of soil organic carbon are lower than their potential capacity.

The significant degradation of crop soils by the oxidation of soil carbon into carbon dioxide started in the 1850's with the introduction of large scale soil cultivation using the mouldboard plough. The effect of ploughing on soil carbon has been measured by Reicosky (1995) for a selection of cultivation techniques (after tilling wheat). Using a mouldboard plough results in soil carbon losses far exceeding the carbon value of the previous wheat crop residue and depleting soil carbon by 1,990 kg/ha compared with a no-tillage system. Furthermore, Lal *et al* (1999) estimated that the global release of soil carbon since 1850 from land use changes has been 136 +/- 55 Pg¹²¹ (billion tonnes) of carbon. This is approximately half of the total carbon emissions from fossil fuels (270 +/- 30 Pg (billion tonnes)), with soil cultivation accounting for 78 +/- 12 Pg and soil erosion 26 +/- 9 Pg of carbon emissions. Lal also estimated that the potential of carbon sequestration in soil, biota and terrestrial ecosystems may be as much as 3 Pg C per year (1.41 parts per million of atmospheric carbon dioxide). A strategy of soil carbon sequestration over a 25-50 year period could therefore have a substantial impact on lowering the rate at which carbon dioxide is rising in the atmosphere providing the necessary time to adopt alternative energy strategies.

Reversing this trend can be achieved by a variety of soil and crop management technologies that increase soil carbon sequestration. These include:

- no-till farming with residue mulch and cover cropping;
- integrated nutrient management (INM), which balances nutrient application with use of organic manures and inorganic fertilizers;
- various crop rotations (including agroforestry);
- use of soil amendments (such as zeolites, biochar, or compost); and
- improved pastures with recommended stocking rates and controlled fire as a rejuvenate method (Lal (2009)).

The production benefits of increasing soil carbon storage include increased soil infiltration, fertility and nutrient cycling, decreased wind and water erosion, minimal soil compaction, enhanced water quality, decreased carbon emissions, impeding pesticide movement and generally enhanced environmental quality. The soil management practices that sequester soil carbon are consistent with a more sustainable and less chemically dependent agriculture (Reicosky (2004)).

¹²¹ 1 Pg of soil carbon pool equates to 0.47 parts per million, of atmospheric carbon dioxide.

Quantification of the impacts of tillage on carbon stocks is complex due to the combination and complexities of soil, climate and management conditions, especially crop type and rotation.

Issues affecting the levels of carbon sequestration include:

- Soil and climatic factors;
- Shallow sampling may introduce a bias in estimating carbon sequestration in NT;
- Initial soil carbon levels;
- Crop biomass production (soil carbon inputs);
- Organic carbon mineralization (soil carbon outputs);
- Soil erosion and re-deposition on soil organic gains and losses.

A number of researchers have examined issues relating to carbon sequestration and different tillage systems and the following are of note:

- West and Post (2002). This work analysed 67 long-term agricultural experiments, consisting of 276 paired treatments. These results indicate, on average, that a change from conventional tillage (CT) to no-till (NT) can sequester 57 +/- 14 g carbon per square metre per year (grams carbon m⁻² year⁻¹), excluding a change to NT in wheat-fallow systems. The cropping system that obtained the highest level of carbon sequestration when tillage changed from CT to NT was corn: soybeans in rotation (90 +/- 59 grams carbon m⁻² year⁻¹.) This level of carbon sequestration equates to 900 +/- 590 kg/carbon/ha/yr, which would have decreased carbon dioxide level in the atmosphere by 3,303 +/- 2,165 kg of carbon dioxide per ha/year¹²²;
- Johnson *et al* (2005) summarised how alternative tillage and cropping systems interact to sequester soil organic carbon (SOC) and impact on GHG emissions from the main agricultural area in central USA. This analysis estimated that the rate of SOC storage in NT compared to CT has been significant, but variable, averaging 400 +/- 61 kg/carbon/ha/yr);
- Calegari *et al* (2008) conducted a 19 year experiment comparing CT and NT management systems with various winter cover crop treatments in Brazil. The research identified that the NT system led to 64.6% more carbon being retained in the upper soil layer than in the CT system. It also found that using NT with winter cover crops resulted in soil properties that most closely resembled an undisturbed forest (ie, best suited for greenhouse gas storage). In addition, both maize and soybean yields were found to be respectively 6% and 5% higher, under NT, than CT production systems;
- Eagle *et al* (2012) examined the literature on GHG mitigation potential of conservation tillage and NT. Based on 280 field comparisons of soil carbon response to no-till the average mitigation potential was estimated at 1,200 kg of carbon dioxide per hectare per year with a range of -200 to 3,200.
- Olson *et al* (2013) evaluated soil carbon levels over a 24-year period on eroded soils in Southern Illinois that were under a corn and soybeans rotation that used different tillage systems. The NT system stored and retained 7.8 tonnes of carbon per ha more than CT plots.

¹²² Conversion factor for carbon sequestered into carbon dioxide = 3.67.

- Kahlona *et al* (2013) evaluated different tillage practices and the importance of mulching on soil physical properties and carbon sequestration over a period of 22 years. The NT plots consistently resulted in positive effects on soil physical attributes and total carbon concentration;
- Bernoux *et al* (2006) reviewed cropping systems, carbon sequestration and erosion in Brazil. Over 30 years of no-tillage practice carbon levels in topsoil increased. This paper reviewed several studies and identified the rate of carbon storage in the top 40 cm of the soil ranges from 400 to 1,700 kg carbon/ha/year in the Cerrado region. The mean rates of carbon storage in the soil surface area (0-20 cm) varied from 600 to 680 kg carbon/ha/year with the greatest variation in the southern region of -70 to 1,600 kg carbon/ha/year (standard deviation 680 +/- 540 kg carbon/ha/year). In addition, in Brazilian conditions direct seeding offers the scope for earlier sowing of crops, shortening the total production cycle, facilitating a second crop in the same season. This results in more carbon being returned to the soil;
- IPCC estimates put the rate of soil organic carbon (SOC) sequestration by the conversion from conventional to all conservation tillage (NT and RT) in North America within a range of 50 to 1,300 kg carbon/ha/year (it varies by soil type, cropping system and eco-region), with a mean of 300 kg carbon/ha/year;
- The adoption of NT systems has also had an impact on other GHG emissions such as methane and nitrous oxide which are respectively 23 and 296 times more potent than carbon dioxide. Robertson (2002) and Sextstone *et al* (1985) suggested that the adoption of NT (sequestering SOC) could do so at the expense of increased nitrous oxide production if growers were to increase the use of nitrogen fertiliser in NT production systems;
- Robertson *et al* (2000) measured gas fluxes for carbon dioxide, nitrous oxide and methane and other sources of global warming potential (GWP) in cropped and unmanaged ecosystems over the period 1991 to 1999. They found that the net GWP was highest for conventional tillage systems at 114 grams of carbon dioxide equivalents/ha/year compared with 41 grams/ha/year for an organic system with legumes cover and 14 grams/ha/year for a no-till system (with liming) and minus 20 grams/ha/year for a NT system (without liming). The major factors influencing the beneficial effect of no-till over conventional and organic systems is the high level of carbon sequestration and reduced use of fuel resulting in emissions of 12 grams of carbon dioxide equivalents m⁻² year⁻¹ compared with 16 grams in conventional tillage and 19 grams for organic tillage. The release of nitrous oxide in terms of carbon dioxide was equivalent in the organic and NT systems due to the availability of nitrogen under the organic system compared with the targeted use of nitrogen fertiliser under the NT systems;
- The importance of nitrogen fixing legume grain crops has also been investigated by Almaraz *et al* (2009). They studied the GHG emission associated with N₂ fixing soybean grown under CT and NT tillage systems. Their findings suggest that using NT in N-fixing legume crops may reduce both carbon dioxide and N₂O emissions in comparison to CT, because in the CT system, harvest residue is incorporated into the soil during ploughing (increasing N₂O emissions);
- Omonode *et al* (2011) assessed N₂O emissions in corn following three decades of different tillage and rotation systems. Seasonal cumulative N₂O emissions were significantly lower by 40%-57% under NT compared to long term chisel and mouldboard plough tillage systems, due to soil organic C decomposition associated with higher levels of soil residue mixing and higher soil temperatures;

- Using IPCC emission factors, Johnson *et al* (2005) estimated the offsetting effect of alternative fertiliser management and cropping systems. For a NT cropping system that received 100 kg N per ha per year (net from all sources), the estimated annual nitrous oxide emission of 2.25 kg N per ha per year would have to increase by 32%-97% to completely offset carbon sequestration gains of 100-300 kg per ha per year;
- Baker *et al* (2007) expressed caution with the premise that NT results in positive carbon sequestration compared with CT. Their analysis identified 37 out of 45 studies (from 17 experiments) with sampling depth <30 cm at which NT treatments (82%) reported more SOC than in the CT control with a mean annual SOC gain of 380 +/- 720 kg/ha/yr. In contrast, in 35 of 51 studies (from 5 experiments) with sampling depths >30 cm, the NT treatments registered less SOC relative to CT with a mean annual loss of -230 +/- 970 kg/ha/yr. In both cases, however, the standard error associated with the estimates was so large that the mean (impact of tillage) was not considered to be significant;
- Research by Angers and Eriksen-Hamel (2008) and Blanco-Canqui and Lal (2008) found that the majority of SOC increase under NT is in the top 10 to 15 cm of soil with insignificant changes (or even decreases) in SOC relative to CT at depths over 15 cm. Hence, newly sequestered carbon in a NT system is accumulated where it is most vulnerable to environmental and management pressures. This makes any permanent increase in SOC associated with NT systems vulnerable to changes in environmental pressures and soil management practices;
- Angers and Eriksen-Hamel's (2008) work also compared NT and full-inversion tillage (FIT) trials and found that while there was a statistically significant increase in total SOC stocks under NT (100.3 versus 95.4 Mg C ha⁻¹ for NT and FIT respectively in the upper 10 cm), to the 21-25 cm soil depth (which corresponds to the mean ploughing depth (23 cm)), the average SOC content was significantly greater under FIT than NT. It was also greater under FIT just below the average depth of ploughing (26-35 cm). However, overall there was significantly more SOC (4.9 Mg ha⁻¹) under NT than FIT across all depths and this difference in favour of NT increased weakly with the duration of the experiment;
- Syswerda *et al* (2011) examined whether soil sequestration gains in the surface layer may result in soils losing carbon at depth under NT compared with CT. Results indicated that surface soil carbon concentrations and total carbon pools were significantly greater under NT than CT. No difference in soil carbon at depth was identified although carbon levels were found to be variable. Also there was no evidence of carbon gains in the surface soils of NT being either offset or magnified at depth;
- Al-Kaisi (2005) evaluated the effects of different tillage systems on soil organic carbon (SOC) and nitrogen (SON), residue carbon and nitrogen inputs and crop (corn and soybean) yields in Iowa. Yields of both corn and soybean were comparable in NT and mouldboard tillage systems but in NT and strip-tillage there was a significant increase in SOC of 14.7% and 11.4% respectively. Changes in SON due to tillage were similar to those observed with the SOC experiments;
- The corn-soybean rotation in the US offers the opportunity for considerable carbon sequestration under NT systems. Hollinger *et al* (2005) measured the carbon flux from 1997 to 2002 to evaluate the carbon budget for corn and soybean in rotation that had been in NT cultivation for over 14 years. The carbon sink when planted with corn was 576 g C m⁻² per year and soybean 33 g C m⁻² per year. Accounting for 100% grain consumption, corn acts as a C-sink of 184 g C m⁻² per year while soybean becomes a C-source of 94 g C

m² per year. As these crops are generally grown in rotation, this system is a net sink of 90 g C m² per year;

- Long term research comparing CT with NT has demonstrated that NT results in higher soil carbon and nitrogen contents, microbial biomass and enzyme activities at the 0-5 cm depth (Mathew *et al.* (2012)). NT soils are more biologically active and diverse, have higher nutrient loading capacities, release nutrients gradually and continuously and have better soil structure than reduced or cultivated soils (Clapperton, J. (2003)). By enhancing the organic matter a higher Carbon-Stock Equilibrium (CSE) can be achieved;
- Bernacchi *et al* (2005) estimate that if the total area of corn/soybeans in the US converted to no-till, 21.7 Tg C (21.7 million tonnes) would be sequestered annually (approximately 350 kg/C/ha/yr), an offset of about 2% of annual USA carbon emissions;
- The most effective natural method of achieving soil carbon sequestration is by the absorption of atmospheric carbon dioxide in plants by photosynthesis, where plants convert carbon dioxide into plant tissue (lignin and carbohydrates) and oxygen. When a plant dies, a portion of the stored carbon is left behind in the soil by decomposing plant residue (eg, roots, stalks) and a larger portion is emitted back into the atmosphere. This plant residue carbon pool contributes 20% to 23% of the total carbon present in maize-based agricultural ecosystems. Short-term carbon sequestration estimates largely reflect plant residue carbon pool changes which are driven by crop inputs and net decomposition differences (Kochsiek *et al.* (2012)). Decomposition rates tend to be proportional to the amount of organic matter, the physiochemical and microbial properties of the soil;
- The potential for maximising soil sequestration tends to be higher in degraded/desertified soils, and soils that have been managed with extractive farming practices, than it is in good-quality soils that have been managed according to recommended management practices (RMPs). Thus, converting degraded/desertified soils into restorative land and adopting RMPs can increase the soil carbon pool. The rate of soil carbon sequestration through the adoption of RMPs on degraded soils ranges from 100 kg/ha per year in warm and dry regions to 1,500 kg/ha per year in cool and temperate regions. Lal R (2010) estimated the technical potential of soil organic carbon sequestration through adoption of RMPs for world cropland soils (1.5 billion ha) to be 0.6 billion to 1.2 billion tonnes of carbon per year and about 3 billion tonnes of carbon per year in soils of all ecosystems (eg, cropland, grazing land, forest lands, degraded lands and wetlands).
- In some cases, intermittent tillage, during long-term RT or NT is needed to reduce soil compaction, for weed control, or to reduce pests or pathogens. While intermittent tillage can cause a decrease in soil stocks, up to 80% of soil gains from NT practices can be maintained when implementing NT with intermittent tillage (Conant *et al* (2007); Venterea *et al* (2006)).

Some studies have questioned the accuracy and the level of carbon sequestered previously projected for NT compared with CT (eg Virto *et al* (2012)). Yang *et al* (2013) concluded that NT has been widely adopted because it reduces labour, fuel and machinery costs, conserves water, and reduces soil erosion which has contributes to improved soil quality and agricultural sustainability. However, it may not be appropriate to attribute all the higher carbon content in the surface of NT soil to either increased carbon input or reduced carbon mineralization (output) relative to CT, when the differences may be due to soil erosion.

Lastly, Powlson *et al* (2014) questioned the assumptions of the UN Emissions Gap Report 2013 which presented a case that additional adoption of NT could further contribute to more carbon sequestration because much of the most suitable land for adoption of NT is already using this production system. Powlson did, however, acknowledge that widespread adoption of NT in North and South America had delivered important carbon sequestration savings and if this land was to revert to CT, it would result in significant carbon release.

The discussion above illustrates the difficulty in estimating the contribution NT systems can make to soil carbon sequestration. The modelling of soil carbon sequestration is also made more difficult by the dynamic nature of soils, climate, cropping types and patterns. If a specific crop area is in continuous NT crop rotation, the full SOC benefits described above can be realised. However, if the NT crop area is returned to a conventional tillage system, a proportion of the SOC gain will be lost. The temporary nature of this form of carbon storage will only become permanent when farmers adopt a continuous NT system which itself tends to be highly dependent upon effective herbicide-based weed control systems.

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