GM crops: global socio-economic and environmental impacts 1996-2020

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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 15th 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 changes[1].

The work contained in this paper has been submitted and accepted for publication in the peer reviewed publication GM Crops and Food. The length of this paper, at over 200 pages, is too long for acceptance for publication as a single document in peer reviewed journals. Therefore, the author submitted three papers focusing separately on the economic impacts, the environmental impacts associated with pesticide use change and the environmental impacts associated with carbon dioxide emissions. The economic impact paper is available in volume 13, 2022-issue 1, p 171-195. http://doi.org/10.1080/21645698.2022.2105626. The environmental impact associated with pesticide use paper is DOI: 10.1080/21645698.2022.2118497 and the environmental impact associated with carbon emissions paper is DOI: 10.1080/21645698.2022.2118495. These two later papers will be published in the next edition of the journal but are available on the journal's website under current research (this status recorded in early October 2022). All papers are available on open access. These papers follow on from numerous previous peer reviewed papers by the author on the subject of crop biotechnology impact[2].

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[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, the last global impact report covering the years 1996-2018 can be found in the GM Crops journal. The environmental impact paper is available at GM Crops & Food, 11:4, 215-240, DOI: 10.1080/21645698.2020.1773198. The economic impact paper is GM Crops & Food, 11:4, 242-261, DOI: 10.1080/21645698.2020.1779574. See also www.pgeconomics.co.uk for a full list of these peer review papers

Executive summary and conclusions

This report presents the findings of research into the global socio-economic and environmental impact of genetically modified (GM) crops in the twenty-five 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 effects[3]

GM technology has had a significant positive impact on farm income derived from a combination of enhanced productivity and efficiency gains (Figure 1 and Figure 2). In 2020, the direct global farm income benefit from GM crops was $18.8 billion. This is equivalent to having added 5.9% to the value of global production of the four main crops of soybeans, maize, canola and cotton. Since 1996, farm incomes have increased by $261.3 billion.

The largest gains in farm income in 2020 have arisen in the maize sector, largely from yield gains. The $3.7 billion additional income generated by GM insect resistant (GM IR) maize in 2020 has been equivalent to adding 6.3% to the value of the crop in the GM crop growing countries, or adding, the equivalent of 2.8% to the $133 billion value of the global maize crop in 2020. Cumulatively since 1996, GM IR technology has added $67.8 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 2020, cotton farm income levels in the GM adopting countries increased by $3.94 billion and since 1996, the sector has benefited from an additional $73.11 billion. The 2020 income gains are equivalent to adding 12.1% to the value of the cotton crop in these countries, or 12% to the $32.7 billion value of total global cotton production. This is a substantial increase in value added terms for two categories of cotton seed technology.

Significant increases to farm incomes have also resulted in the soybean and canola sectors. The GM herbicide tolerant (HT) technology in soybeans has boosted farm incomes by $5.64 billion in 2020, and since 1996 has delivered $74.65 billion of extra farm income. The adoption of ‘Intacta’ soybeans (combining HT and IR traits) in South America since 2013 also provided $16 billion of additional farm income. In the canola sector (largely North American) an additional $8.2 billion has been generated (1996-2020).

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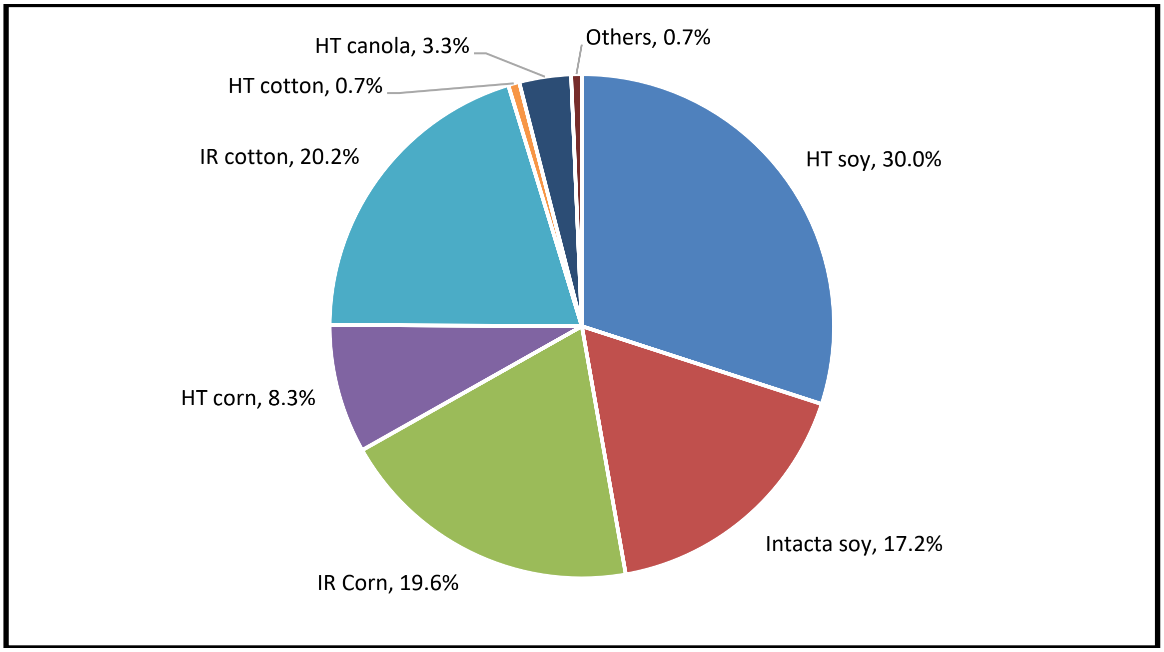
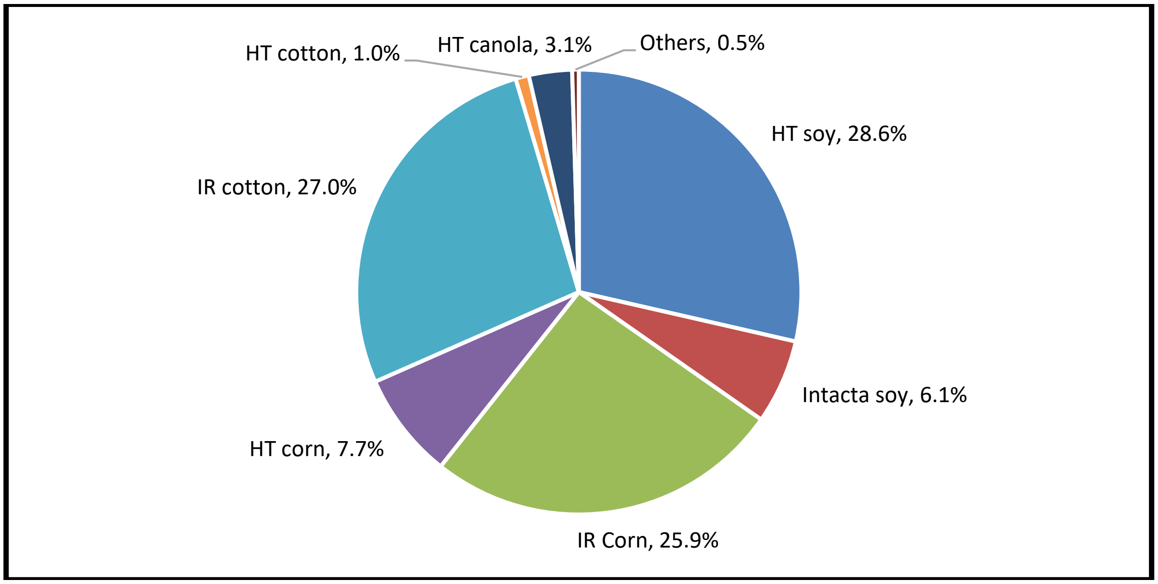
[3] See section 3 for details

Figure 1: Global GM crop farm income benefits 2020: baseline total $18.8 billion



Notes: Others = HT sugar beet, Virus resistant papaya and squash, drought tolerant maize and IR brinjal

Figure 2: Cumulative global GM crop farm income benefits 1996-2020: baseline total $261.3 billion



Notes: Others = HT sugar beet, Virus resistant papaya and squash, drought tolerant maize and IR brinjal

Figure 3 and Figure 4 summarise farm income impacts in key GM crop adopting countries. These highlight 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 the range GM crop adoption in the US. Figure 4, in particular (the increasing share of 'other countries') also illustrates the growing level of farm income benefits being obtained in countries that were later adopters of GM crop technology such as Pakistan, the Philippines and Colombia.

Figure 3: Cumulative global GM crop farm income benefits 1996-2020 by country: baseline total $261.3 billion

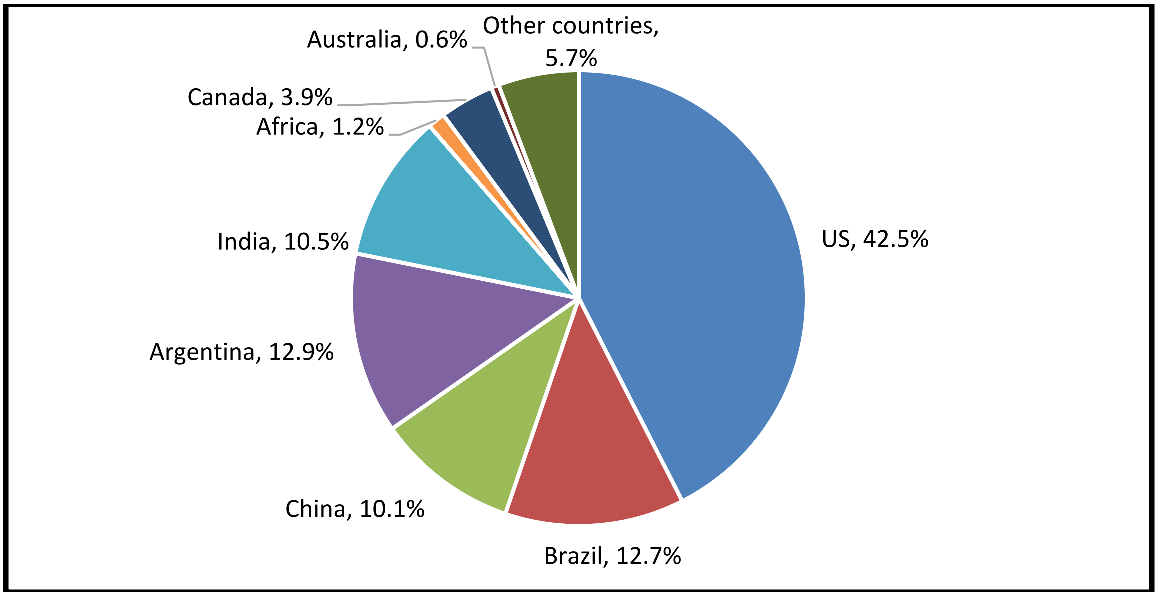
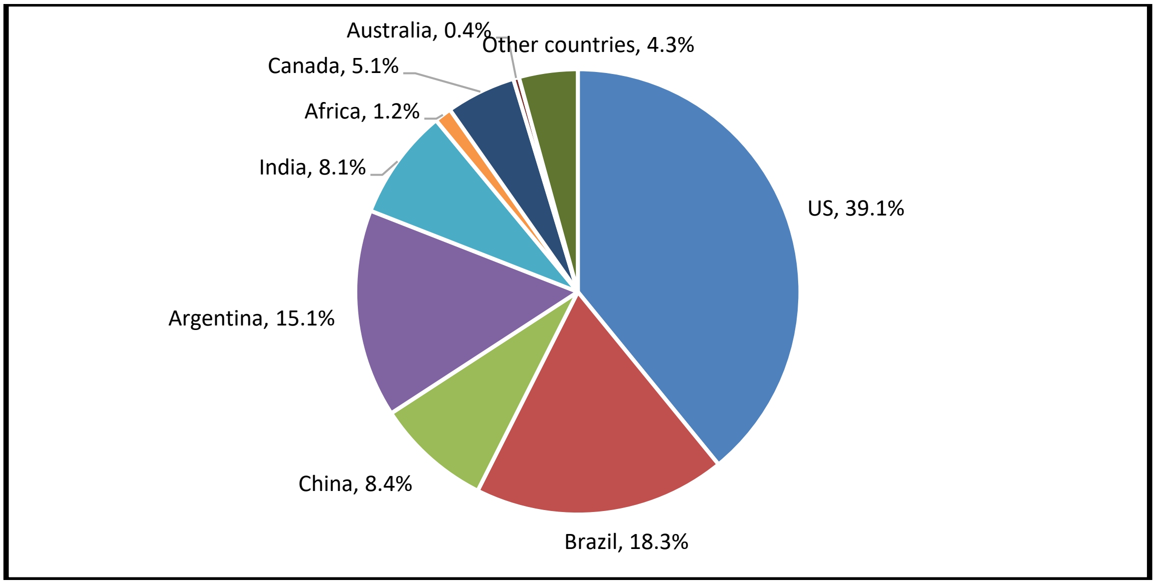


Figure 4: Global GM crop farm income benefits 2020 by country: baseline total $18.8 billion



In terms of the division of the economic benefits obtained by farmers in developing countries relative to farmers in developed countries, in 2020, 55% of the farm income benefits have been earned by developing country farmers. The vast majority of these income gains for developing country farmers have been from GM IR cotton and GM HT soybeans[4]. Over the twenty-five

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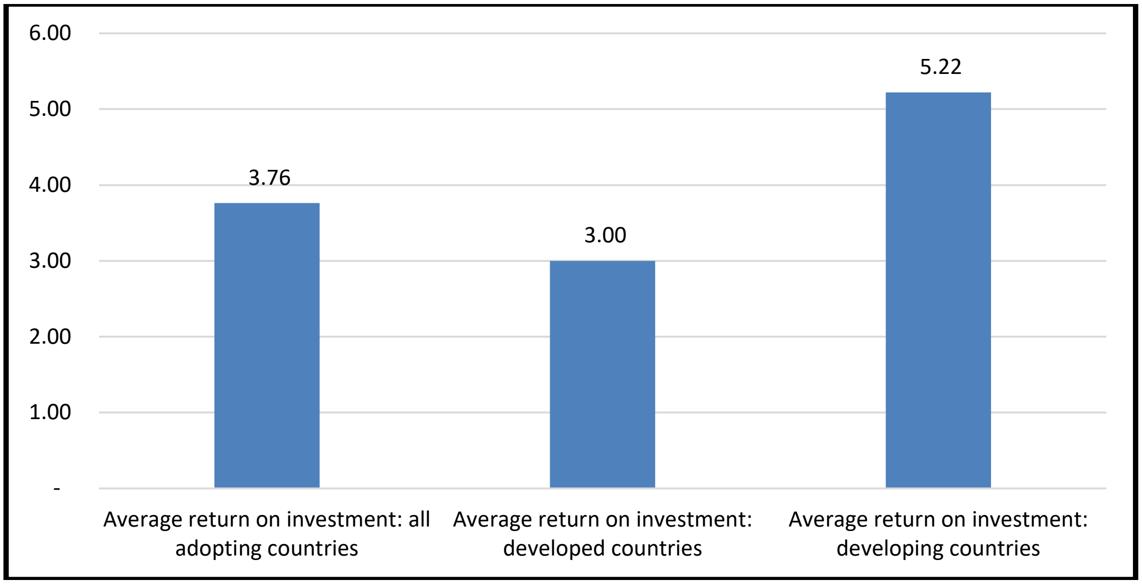
[4] The authors acknowledge that the classification of different countries into developing or developed country status affects the distribution of benefits between these two categories of country. The definition used in this paper is consistent with the definition used by James (2014)

years, 1996-2020, the cumulative farm income gain derived by developing country farmers was 52% ($136.6 billion).

Examining the cost farmers pay for accessing GM technology, the average cost to farmers (1996-2020) was equal to 27% of the total technology gains (inclusive of farm income gains plus cost of the technology payable to the seed supply chain[5]). In terms of investment, this means that for each extra dollar invested in GM crop seeds (relative to conventional seed costs), farmers gained an average $3.76 in extra income. In developing countries, the average return was $5.22 for each extra dollar invested in GM crop seed and in developed countries the average return was $3.00 (Figure 5).

For farmers in developing countries the total cost was equal to 19% of total technology gains, whilst for farmers in developed countries the cost was 33% of the total technology gains. Although, circumstances vary between countries, the higher share of total technology gains accounted for by farm income gains in developing countries, relative to the farm income share in developed countries, reflects factors such as weaker provision and enforcement of intellectual property rights in developing countries and the higher average level of farm income gain on a per hectare basis derived by developing country farmers relative to developed country farmers.

Figure 5: Average return on investment per extra $ spent on GM traited-seed 1996-2020 $/ha



Seventy-two per cent of the total income gain over the 25-year period derives from higher yields and second crop soybean gains with 28% from lower costs (mostly from lower pest and weed control costs). The balance of the income gain arising from yield/production gains relative to cost savings is changing as second-generation GM crops are increasingly adopted. Thus in 2020 the split of total income gain came 91% from yield/production gains and 9% from cost savings.

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[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

Production effects of the technology

Based on the yield impacts used in the direct farm income benefit calculations above and taking account of the second soybean crop facilitation in South America, GM crops have added important volumes to global production of maize, cotton, canola and soybeans since 1996 (Table 1).

The GM IR traits, used in maize and cotton, have accounted for 91.1% of the additional maize production and 98.2% 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 25 years since 1996 has been +17.7% for maize and +14.5% for cotton.

As indicated earlier, the primary impact of GM HT technology has been to provide more cost effective (less expensive) and easier weed control, as opposed to improving yields, the improved weed control has, nevertheless, delivered higher yields in some countries. The main source of additional production from this technology has been via the facilitation of no tillage production systems, shortening the production cycle and how it has enabled many farmers in South America to plant a crop of soybeans immediately after a wheat crop in the same growing season. This second crop, additional to traditional soybean production, has added 222.7 million tonnes to global soybean production between 1996 and 2020 with Intacta soybeans adding a further 44.4 million tonnes since 2013. The remaining additional GM-related soybean production has come from the second generation of GM HT soybeans grown in North American countries since 2008 and where the GM HT technology has enabled farmers to obtain higher yield via improved levels of weed control.

Table 1. Additional crop production arising from positive yield effects of GM crops (million tonnes)

	1996-2020	2020
Soybeans	330.35	33.48
Maize	594.58	47.9
Cotton	37.01	2.26
Canola	15.77	1.00
Sugar beet	1.87	0.15

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

The widespread use of GM crop technology has also contributed to changing agriculture’s land footprint by allowing farmers to grow more on existing land used for agricultural purposes, reducing the pressure to bring in new land into cultivation. For example, if world agriculture wanted to maintain global production of the four main crops in which GM seed technology has been widely used levels at 2020 levels, but without using the GM technology, this would require farmers to plant an additional 11.6 million ha of soybeans, 8.5 million ha of maize, 2.8 million ha of cotton and 0.5 million ha of canola, an area (23.4 million ha in total) equivalent to the combined agricultural area of Philippines and Vietnam. This fits well with the land sharing and sparing approach, that the science and evidence (see for example Balmford, 2021) shows is the best way to deliver a more sustainable global agriculture.

Environmental impact from changes in insecticide and herbicide use[6]
To examine this impact, the study has analysed 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 (Figure 6 and Figure 7). Since 1996, the use of pesticides on the GM crop area was reduced by 748.6 million kg of active ingredient (a 7.2% reduction), and the environmental impact associated with herbicide and insecticide use on these crops, as measured by the EIQ indicator, fell by17.3%.

The largest share of this was accounted for by GM IR cotton (45%) followed by GM HT maize (30%: Figure 6). In terms of the environmental impact associated with herbicide and insecticide use on these crops, as measured by the EIQ indicator, this improved by 17.3%, with the largest share of these improvements delivered by GM IR cotton (about 40% of the total), followed by GM HT soybeans (26%).

At the country level, US farms have seen the largest environmental benefits, with a 322 million kg reduction in pesticide active ingredient use (43% of the total). This is not surprising given that US farmers were first to make widespread use of GM crop technology, and for many years, the GM adoption levels in all four US crops have been in excess of 80%, and insecticide/herbicide use has, in the past been, the primary method of weed and pest control. Important environmental benefits have also occurred in China and India from the adoption of GM IR cotton, with a reduction in insecticide active ingredient use of over 304 million kg (1996-2020).

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[6] See section 4.1

Figure 6: Share of aggregate active ingredient usage (reductions) by trait 1996-2020 (baseline total 748.6 million kg)

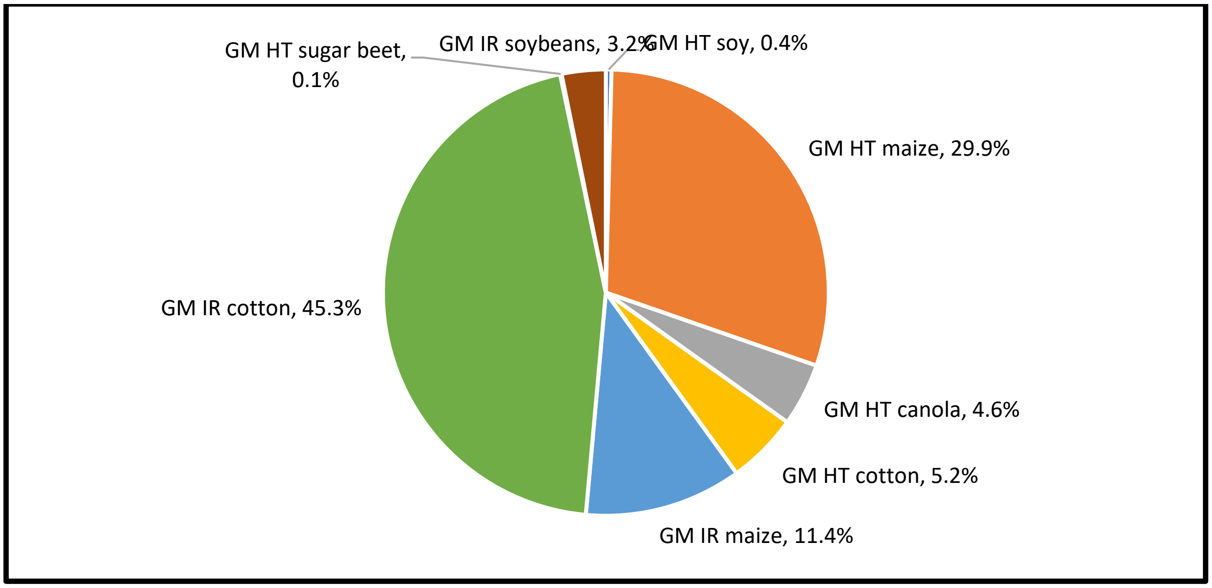
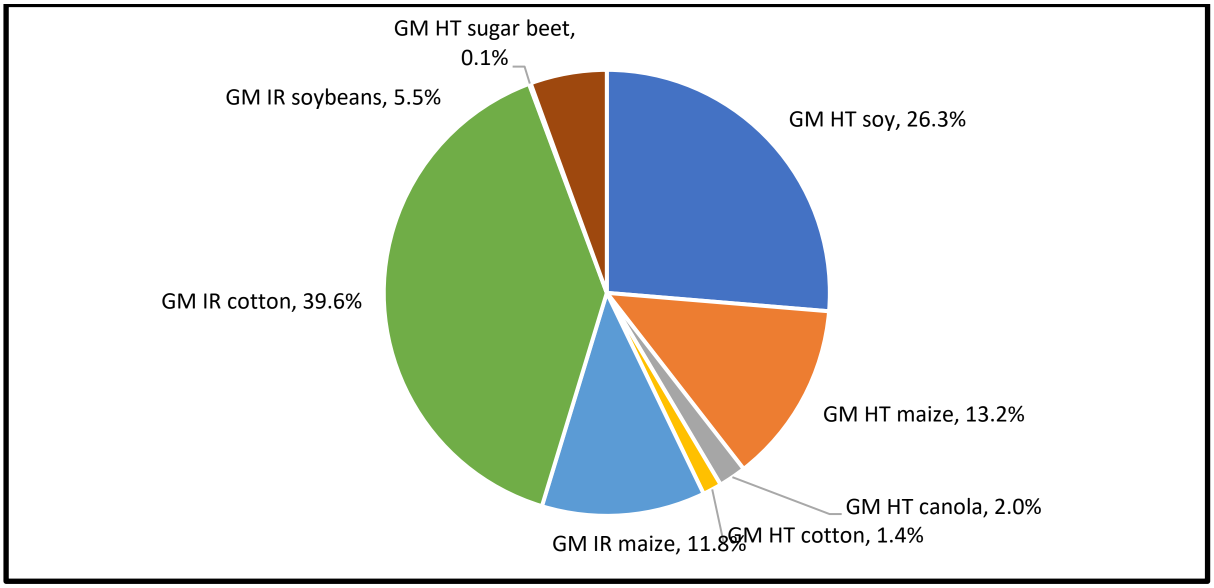


Figure 7: Share of aggregate EIQ changes (improvements) by trait 1996-2020



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 56 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 17 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 60%-80% of the total area annually devoted to maize, cotton, canola, soybeans and sugar beet (the crops in which GM HT technology is used).

Where farmers are faced with the existence of weeds resistant to glyphosate in GM HT crops, they are advised to include other herbicides (with different and complementary modes of action) in combination with glyphosate and, in some cases, to adopt cultural practices such as ploughing in their integrated weed management systems. These changes in weed management practices have been evident from the changes in herbicide usage patterns discussed above and reflect the broader agenda of developing more integrated weed control strategies across all forms of cropping systems (not just GM HT) to minimise and slow down the potential for weeds developing resistance to whatever form of weed control is practiced. In addition, GM HT crops tolerant to other herbicides (often stacked with glyphosate) have become available from 2016 in some countries. At the macro level, these changes have influenced the mix, total amount, cost and overall profile of herbicides applied to GM HT crops in the last 15 years.

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).

Impact on greenhouse gas (GHG) emissions[7]

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

a) Reduced fuel use

The fuel savings arising from making fewer insecticide applications with the use of GM IR crop technology in maize, cotton and soybeans and the switch from conventional tillage (CT) to reduced/no tillage (RT/NT[8]) systems facilitated by GM HT crops, have delivered permanent savings in carbon dioxide emissions. Over the period 1996 to 2020, the cumulative permanent reduction in fuel use has been about 39,147 million kg of carbon dioxide, arising from reduced fuel use of 14,662 million litres. In terms of car equivalents, this is equal to taking 25.9 million cars off the road for a year (Table 2).

The largest fuel use-related reductions in carbon dioxide emissions have come from the adoption of GM HT technology and how it has facilitated a switch to RT/NT production systems with their reduced soil cultivation practices. This accounted for 92% of the fuel and carbon dioxide savings in the period 1996-2020, within which GM HT soybeans accounted for the largest contribution (68% of the total savings). These savings have been greatest in South America.

In 2020, the fuel related savings were 2,330 million kg of carbon dioxide, arising from reduced fuel use of 948 million litres. These savings are equivalent to taking 1.68 million cars off the road for one year.

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[7] See section 4.2

[8] No-till (NT) farming means that ground is hardly disturbed at planting (not ploughed), while reduced tillage (RT) means that ground is disturbed less than it would be with traditional tillage systems. For example, under a NT farming system, soybean seeds are planted through the organic material that is left over from a previous crop such as maize, cotton or wheat. Full definitions are given in section 4.2.2

Table 2: Carbon storage/sequestration from reduced fuel use with GM crops 1996-2020

Crop/trait/country	Fuel saving (million litres)	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)
HT soybeans			
Argentina	4,433	11,837	7,844
Brazil	2,749	7,341	4,865
Bolivia, Paraguay, Uruguay	899	2,401	1,591
US	1,687	4,503	2,984
Canada	255	681	451
HT maize			
US	2,257	6,027	3,994
Canada	121	323	214
HT canola			
Canada: GM HT canola	1,067	2,848	1,887
IR maize			
Brazil	369	984	652
US/Canada/Spain/South Africa	91	243	161
IR cotton – global	285	760	504
IR soybeans – South America	449	1,199	795
Total	***14,662***	***39,147***	***25,942***

Notes:

1. Assumption: an average family car in 2020 produces 123.4 grams of carbon dioxide per km. A car does an average of 12,231 km/year and therefore produces 1,509 kg of carbon dioxide/year
2. GM IR cotton. India, Pakistan, Myanmar and China excluded because insecticides assumed to be applied by hand, using back pack sprayers

b) Additional soil carbon storage/sequestration

There has been significant sequestration (storage) of soil carbon (and therefore lower emissions of carbon dioxide) resulting from the widespread adoption and maintenance of 'no-till' (NT) and 'reduced-till' (RT) farming systems in North and South America. This has been facilitated by the use of GM HT crop technology.

Based on the areas of GM HT crops using RT/NT production systems in North and South America in 2020, we estimate that an extra 5,750 million kg of soil carbon has been sequestered in 2020. This is equivalent to 21,101 million kg of carbon dioxide that has not been released into the global atmosphere. In terms of removing vehicles from the road, these savings are equivalent to taking 14 million cars off the road for one year (Table 3).

Table 3: Context of carbon sequestration impact 2020: car equivalents

Crop/trait/country	Additional carbon stored in soil (million kg of carbon)	Potential additional soil carbon sequestration savings (million	Soil carbon sequestration savings: as average family car equivalents removed

		kg of carbon dioxide)	**from the road for a year ('000s)**
HT soybeans			
Argentina	1,832.5	6,725.2	4,445.8
Brazil	1,485.0	5,450.1	3,611.0
Bolivia, Paraguay, Uruguay	490.7	1,800.8	1,193.1
US	110.9	407.0	269.6
Canada	62.9	230.7	152.9
HT maize			
US	1,481.6	5,437.6	3,602.7
Canada	15.6	57.4	38.0
HT canola			
Canada: GM HT canola	270.4	992.4	657.5
IR maize			
Brazil	0	0	0
US/Canada/Spain/South Africa	0	0	0
IR cotton – global	0	0	0
IR soybeans – South America	0	0	0
Total	***5,749.6***	***21,101.1***	***13,980.7***

If the annual estimates of soil carbon sequestration are aggregated over the 1996-2020 period, then the additional amount of soil carbon sequestered since 1996 has been equivalent to 344,044 million kg of carbon dioxide that has not been released into the global atmosphere, equivalent to taking about 228 million cars off the road over this period. Readers should, however, note that this estimate is likely to significantly overstate the true soil carbon sequestration benefits from the adoption of RT/NT systems over this 25 year period because some of the additional soil carbon sequestration gains from RT/NT systems will have been lost from some subsequent ploughing of land in these crops and production systems.

Overall, 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.

Returning to the 2020 analysis of carbon emission savings from both sources of fuel related savings and soil carbon storage, aggregating these benefits results in the total carbon dioxide savings in 2020 being equal to about 23,631 million kg, equivalent to taking 15.6 million cars off the road for a year. This is equal to 49% of registered cars in the UK.

1 Introduction

This study[9] 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-five years, 1996-2020[10]. 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-five 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.

Environmental impacts associated with:

- Insecticide and herbicide use, including use of the environmental impact measure, the Environmental Impact Quotient (EIQ)[11];
- Greenhouse gas (GHG) emissions.

1.2 Methodology

The report has been compiled based largely on desk research and analysis. A detailed literature review[12] 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 presented[13], 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.

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[9] The authors acknowledge that funding towards the researching of this paper was provided by Bayer Crop Science. The material presented in this paper is, however, the independent view 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 first produced in 2005 and updated regularly, covering the first nine then subsequent 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] Based on Kovach J et al (1992 & annually updated) – see section 4.1 and Appendix 4

[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 and production impact;
- 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-five years, 1996-2020.

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 2020, the global planted area was 185.6 million hectares (ha).

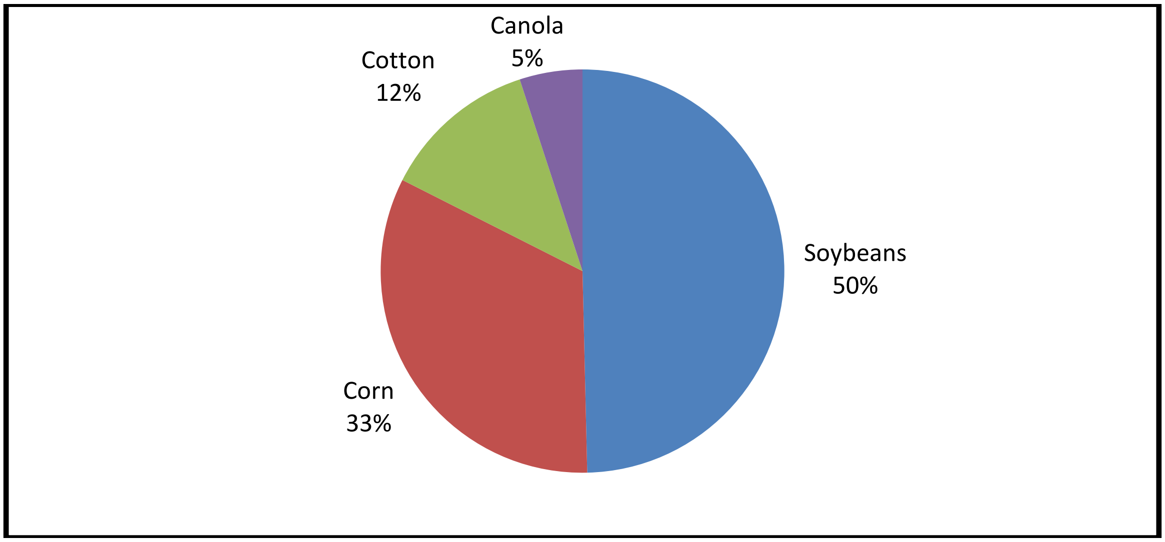
In terms of the share of the main crops in which GM traits have been commercialised (soybeans, maize/corn, cotton and canola), GM traits accounted for 47.4% of the global plantings to these four crops in 2020.

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 8)[14]. In 2020, GM soybeans accounted for the largest share (50%), followed by maize/corn (33%), cotton (12%) and canola (5%).

Figure 8: GM crop plantings 2020 by crop (base area of the four GM crops: 185.6 million ha)



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

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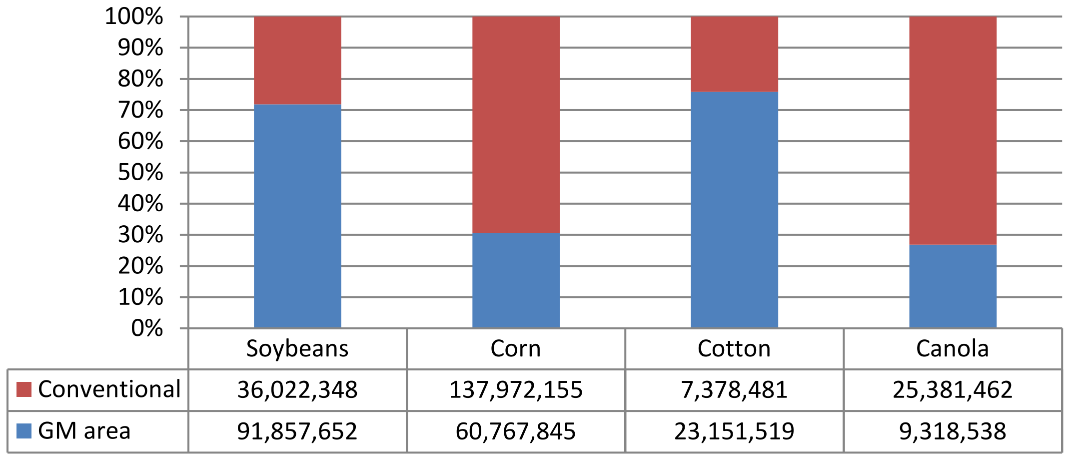
[14] In 2020, there were also additional GM crop plantings of papaya (187 hectares), squash (1,000 hectares), sugar beet (462,300 ha), alfalfa (about 1.26 million ha) and potatoes (1,780 ha) in the US. There were also 9,000 hectares of papaya in China, 17,000 ha of sugar beet in Canada and 6,309 ha of 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 (72%) in 2020. For the other three main crops, the GM shares were 31% for maize, 76% for cotton and 27% for canola (Figure 9).

Figure 9: 2020: share of GM crops in global plantings of key crops (ha)

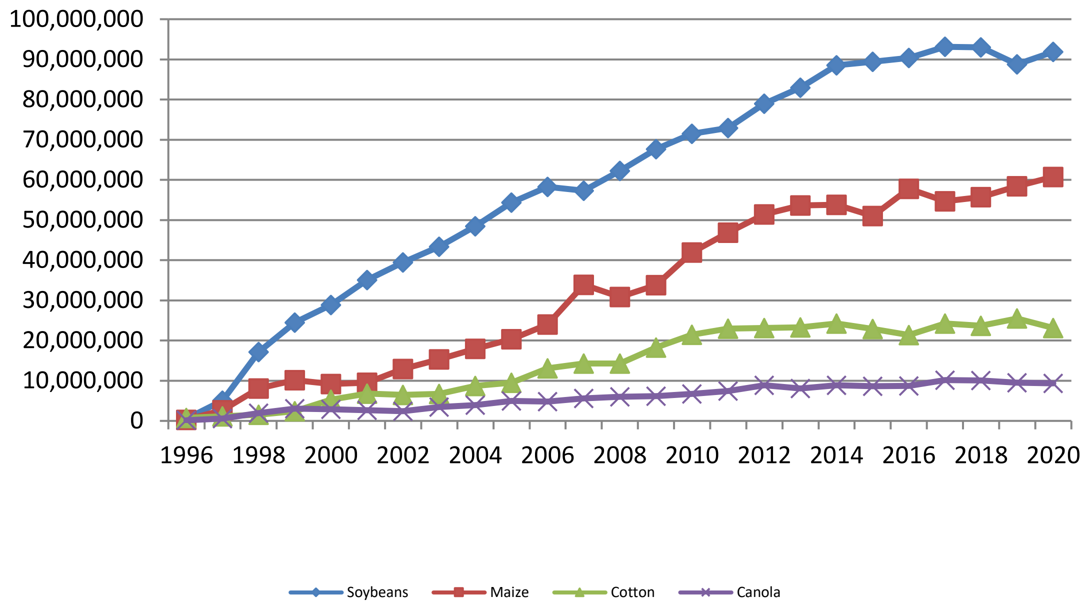


	Soybeans	Corn	Cotton	Canola
🟥 Conventional	36,022,348	137,972,155	7,378,481	25,381,462
🟦 GM area	91,857,652	60,767,845	23,151,519	9,318,538

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

The trend in plantings to GM crops (by crop) since 1996 is shown in Figure 10.

Figure 10: Global GM crop plantings by crop 1996-2020 (ha)

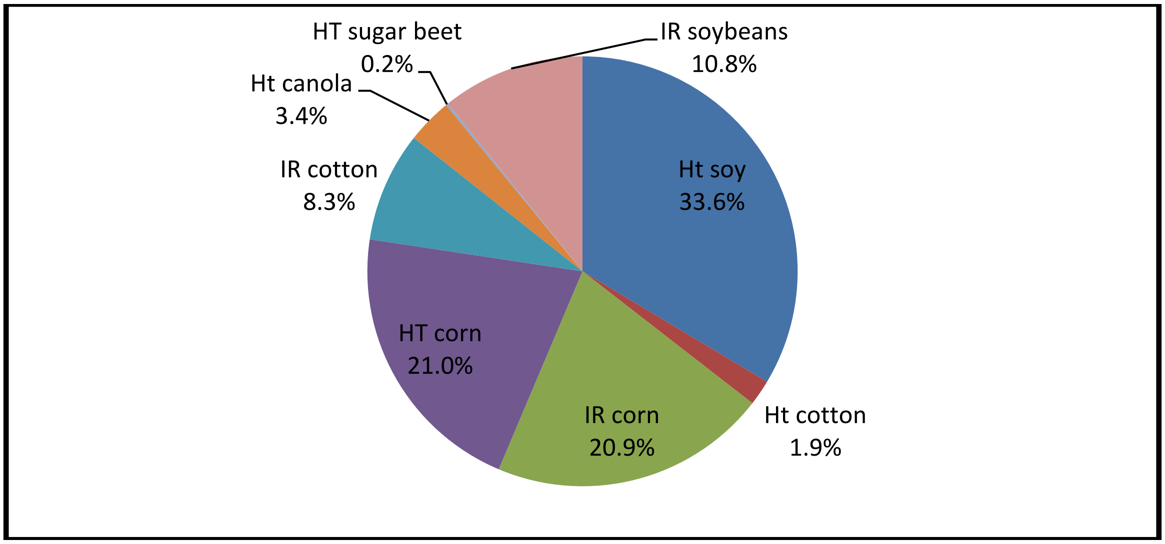


Sources: Various including ISAAA, Canola Council of Canada, CropLife Canada, USDA, CSIRO, ArgenBio, National Ministries of Agriculture (Mexico, Philippines, Spain, Vietnam), Grains South Africa

2.2.2 By trait

Figure 11 summarises the breakdown of the main GM traits planted globally in 2020. GM herbicide tolerant (HT) soybeans dominate, accounting for 33.6% of the total, followed by herbicide tolerant (HT) and insect resistant (IR: largely Bt) maize, IR soybeans (also containing HT technology) and IR cotton with respective shares of 21%, 20.9%, 10.8% and 8.3%[15].

Figure 11: Global GM crop plantings by main trait and crop: 2020



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

2.2.3 By country

The US had the largest share of global GM crop plantings in 2020 (36%), followed by Brazil (30%). The other main countries planting GM crops were Argentina, India, Canada and China (Figure 12).

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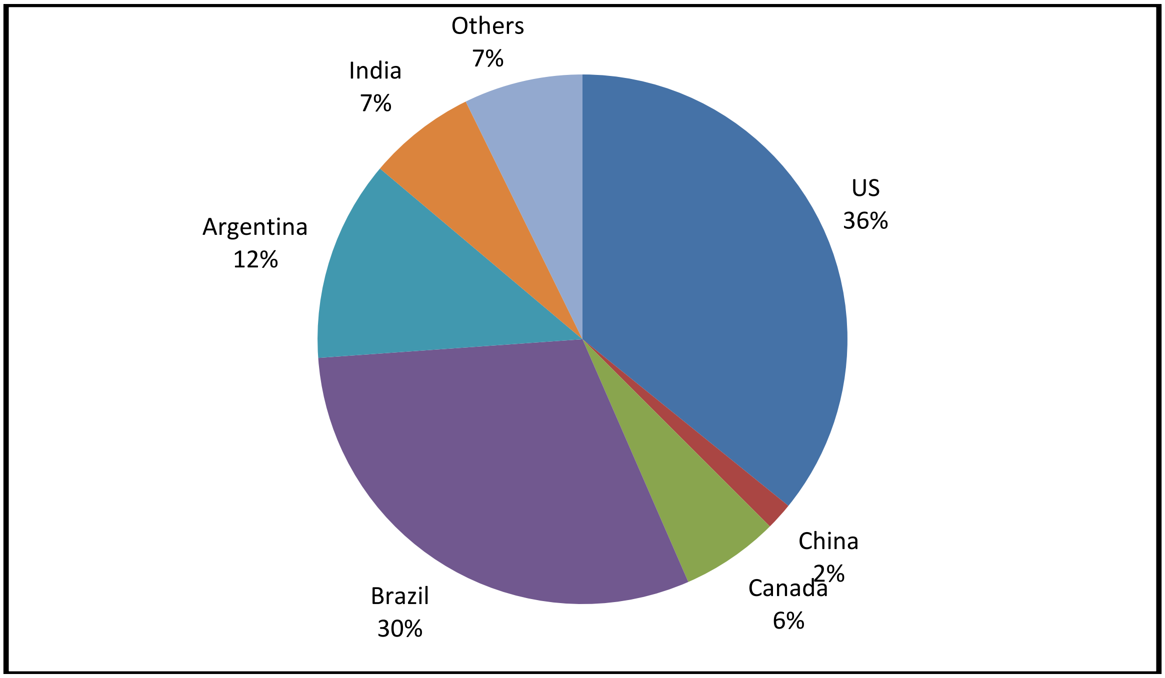
[15] The reader should note that the total plantings by trait produces a higher global planted area (273.4 million ha) than the global area by crop (185.6 million ha) because of the planting of some crops containing the stacked traits of herbicide tolerance and insect resistance

Figure 12: Global GM crop plantings 2020 by country



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

In terms of the GM share of production in the main adopting countries, Table 4 shows that, in 2020, 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 continued to 2020. All of the US sugar beet crop also used GM HT technology in 2020;
- *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 country 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 cotton crop (16,200 ha in 2020);
- *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 2020. 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 95% of the crop in 2020. GM virus resistant papaya has also been used in China since 2008. In India, IR cotton was first adopted in 2002, and its use increased rapidly in subsequent years, so that in 2020 this technology continues to

dominate total cotton production (94% 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. Vietnam adopted IR/HT maize in 2015 and 10% of the crop used seed containing this technology in 2020. Lastly, virus resistant brinjal has been grown in Bangladesh since 2014;

- 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. 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) have been grown in Brazil, Paraguay, Argentina and Uruguay since 2013.

Table 4: GM share of crop plantings in 2020 by country (% of total plantings)

	Soybeans	Maize	Cotton	Canola
US	94	92	96	97
Canada	86	90	N/a	89
Argentina	97	99	100	N/a
South Africa	95	83	100	N/a
Australia	N/a	N/a	100	25
China	N/a	N/a	95	N/a
Philippines	N/a	27	N/a	N/a
Paraguay	99	72	100	N/a
Brazil	96	93	88	N/a
Uruguay	99	90	N/a	N/a
India	N/a	N/a	94	N/a
Colombia	N/a	58	56	N/a
Mexico	Nil	N/a	97	N/a
Bolivia	97	N/a	N/a	N/a
Vietnam	N/a	10	N/a	N/a
Pakistan	N/a	N/a	95	N/a
Myanmar	N/a	N/a	89	N/a

Notes: N/a = not applicable. Colombia maize % adoption relates to commercial maize area only, excluding subsistence maize crop

3 The farm level economic impact of GM crops 1996-2020

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 years[16]. 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;

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[16] 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))

- 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 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 labour[17]), crop quality (eg, improvements in quality arising from less pest damage or lower levels of weed impurities which result in price premia being obtained from buyers) and the scope for facilitating the planting of a second crop in a season (eg, second crop soybeans in Argentina following wheat that would, in the absence of the GM HT seed, probably not have been planted). Thus, the farm income effect measured is essentially a gross margin impact (impact on gross revenue, less variable costs of production) rather than a full net cost of production assessment. Through the inclusion of yield impacts and the application of actual (average) farm prices for each year, the analysis also indirectly takes into account the possible impact of 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

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[17] 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

research are summarised[18] and extrapolated to the cumulative biotech crop planted areas in the US over the period 1996-2020.

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 crops

GM HT crops were amongst the first to be widely grown, with most largely tolerant to the herbicide active ingredient glyphosate. The main economic impact of this technology has been to provide more cost effective (less expensive) and easier weed control for farmers. Nevertheless, some users of this technology have also derived higher yields from better weed control (relative to weed control obtained from conventional technology). As detailed in the following sub-sections, the impact varies by country and year, and is due to several factors. These include the changing costs of different weed control systems used in GM HT versus conventional (non-GM) crops, which may include different/alternative herbicides and/or other forms of weed control (eg, hand or mechanical weeding), the mix and amounts of herbicides applied, the cost farmers pay for accessing the GM HT technology and levels of weed problems faced by farmers. In turn, there are a number of important and changing variables affecting the mix and cost of different weed control systems used:

- The mix and amounts of herbicides used are affected by price and availability of herbicides. Herbicides used include both 'older' products that are no longer protected by patents and newer 'patent-protected' chemistry, with availability affected by commercial decisions of suppliers to market or withdraw products from markets and regulation (eg, changes to approval processes and the imposition of restrictions/bans). Prices also vary by year and country;
- The amount farmers pay for use of the technology varies by country and year. Pricing of technology (all forms of seed and crop protection technology, not just GM technology) varies according to the level of benefit that farmers are likely to derive from it. In addition, it is influenced by intellectual property rights (patent protection, plant breeders' rights and rules relating to use of farm-saved seed). In countries with weaker intellectual property rights, the cost of the technology tends to be lower than in countries where there are stronger rights. Also, the HT technology available in 2020 is, in some countries, not the same as the technology available in the early years of adoption. In the first 15-20 years of widespread use of GM HT crop technology, crops tolerant to glyphosate dominated. In 2020, some farmers, notably in North America, now have the option of using seed tolerant to glyphosate plus other active ingredients like glufosinate, 2 4 D and dicamba. These forms of 'stacked' tolerances are typically more expensive than the single herbicide tolerance traits of the early years of use;

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[18] Notably relating to the US - Marra and Piggott (2006)

- Where GM HT crops tolerant to glyphosate have been widely grown for a number of years, some incidence of weed resistance to glyphosate has occurred and resistance has become a major concern in some regions. Detailed discussion of this issue is presented in section 4 (environmental impacts). From a farm economic perspective, this resulted in growers of GM HT crops increasingly including other herbicides (with different and complementary modes of action) in combination with glyphosate in their weed management systems. In addition, in the last 4-5 years, the increasing array of new GM HT technology referred to above has entered the market offering farmers (notably in the US and Canada in 2020) crops that are tolerant to other herbicide active ingredients typically in combination with tolerance to glyphosate (and sometimes offering tolerance to three active ingredients). At the macro level, these changes have influenced the mix, total amount, cost and overall profile of herbicides applied to GM HT crops. It has also resulted in the weed control costs associated with growing GM HT crops generally being higher in 2020 than in the early 2000s. However, relative to the conventional alternative, GM HT crops have continued to offer important economic advantages for most users, either in the form of lower costs of production or higher yields (arising from better weed control). An important contributory factor to this (maintenance of cost saving advantage of GM HT systems versus conventional alternatives) is that many of the herbicides used in conventional production systems also face significant weed resistance issues themselves (in the mid-1990s this was one of the reasons why glyphosate tolerant soybeans were rapidly adopted, as glyphosate provided good control of these weeds).

These points are further illustrated in the analysis below.

3.1.1 GM HT soybeans

3.1.1.1 The US

First generation GM HT soybeans
In 2020, 94% (33.3 million ha) of the total US soybean crop was planted to seed with GM HT traits. Of this, 3.8 million ha (11% of the total GM HT crop) were first generation GM HT soybeans. The farm level impact of using this technology since 1996 is summarised in Figure 13.

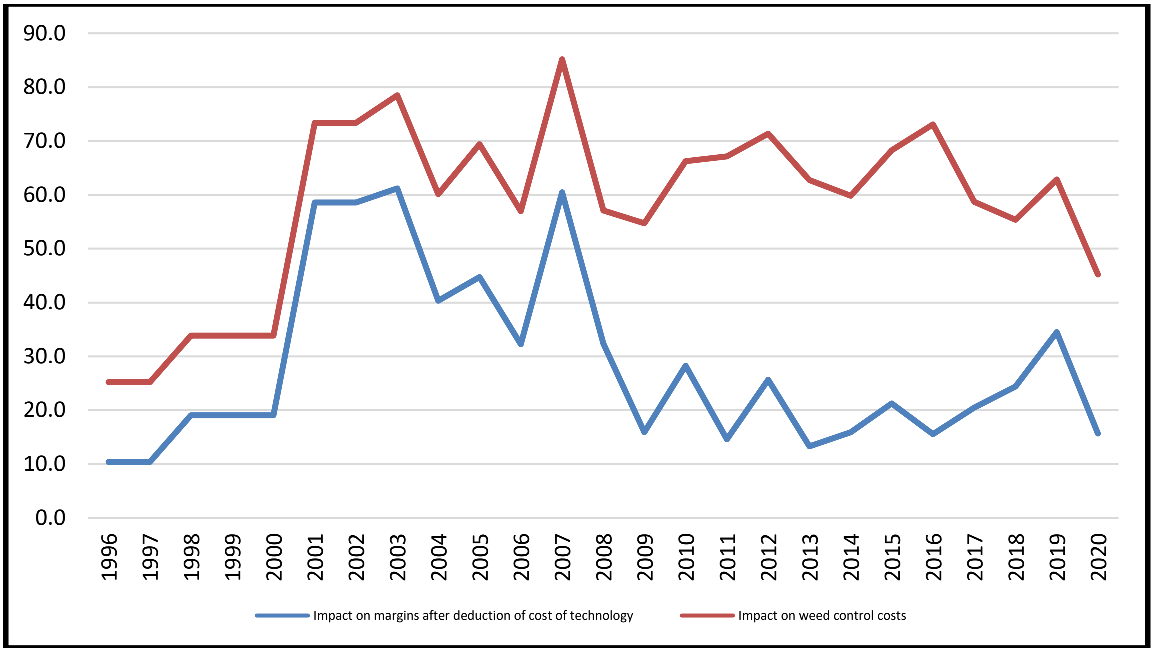
The key features are as follows:

- The primary impact has been to reduce the cost of weed control, with the annual savings being within a range of between $25/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). Of note are the periods immediately after 2000, when glyphosate was no longer patent protected in the US, resulting in increased availability of alternative (generic) and cheaper glyphosate and the period between 2008 and 2010, when there was a significant increase in the global price of glyphosate relative to increases in the price of other herbicides (commonly used on conventional soybeans). In addition, the problem of weed species becoming resistant to glyphosate and to other herbicides used in soybean production (both GM HT and conventional) during the last 20 years has influenced the mix, volume; cost and overall profile of herbicides applied to both forms of production;
- Against the background of underlying improvements in average yield levels over the 1996-2020 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 has been neutral[19];

- 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 and eventually declined as the total area planted to this trait has fallen in line with increased adoption of second-generation GM HT soybeans (see below). In 2020, the total income gain from first generation HT soybeans was $58.8 million. The cumulative farm income benefit over the 1996-2020 period (in nominal terms) was $14.06 billion.

Figure 13: Farm level savings of using GM HT soybeans (first generation) in the US 1996-2020 ($/ha)



Sources and notes:

1. Impact data 1996-1997 based on Marra et al (2002), 1998-2000 based on Carpenter and Gianessi (1999) and 2001-2007 based on Sankala & Blumenthal (2003 & 2006), Johnson and Strom (2008). 2008 onwards own calculations based on commonly used weed control programmes and current (each year) prices of herbicides. The weed control systems, usage levels and prices are drawn from a combination of extension services and Kynetec annual farmer (survey) data
2. 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

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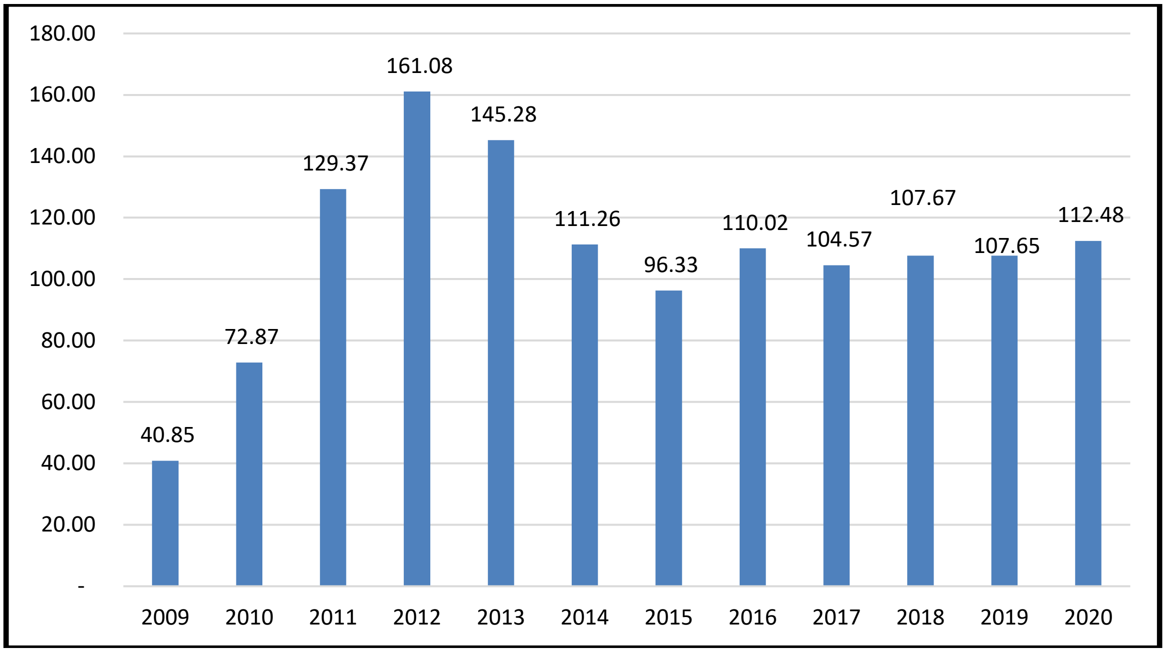
[19] Some early studies of the impact of GM HT soybeans in the US suggested that GM HT soybeans produced lower yields than conventional soybean varieties. Where this may have occurred, it applied only in early years of adoption, when the technology was not present in all leading varieties suitable for all of the main growing regions of the US. 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

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 27.6 million ha in 2020 (83% 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%. 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 performance[20] 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 reported average yield improvements of about +5%. In subsequent years, the average yield gains reported were higher in the range of +9% to +11% 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 between $50/ha and $67/ha (average $55.5/ha until 2018 but having fallen to +$30/ha in 2020), the net impact on farm income in 2020, inclusive of yield gain, was +$112/ha (Figure 14). Aggregated to the national level this was equal to an improvement in farm income of $3.1 billion in 2020 and cumulatively since 2009, the total farm income gain has been $22.8 billion.

Figure 14: Average farm income gain from using 2nd generation GM HT soybeans in the US 1996-2020 ($/ha)



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[20] The authors are not aware of any survey-based assessment of performance in 2009

3.1.1.2 Argentina

As in the US, first generation GM HT soybeans were planted commercially from 1996. Since then, use of the technology has increased rapidly and almost all soybeans grown in Argentina are GM HT (97.1%) in 2020. 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 (Figure 15). 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-\$57/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 HT first generation 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 \$14-\$33/ha. Net income gains have been in the range of \$14/ha-\$30/ha;
- The net income gain from use of the GM HT technology at a national level was \$227 million in 2020. Since 1996, the cumulative benefit (in nominal terms) has been \$7.5 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. Thirty-two per cent of the total Argentine soybean crop was second crop in 2020[21], 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 \$1.4 billion in 2020 and \$16.6 billion cumulatively since 1996;
- The total farm income benefit inclusive of the second cropping was \$1.65 million in 2020 and \$24.1 billion cumulatively between 1996 and 2020.

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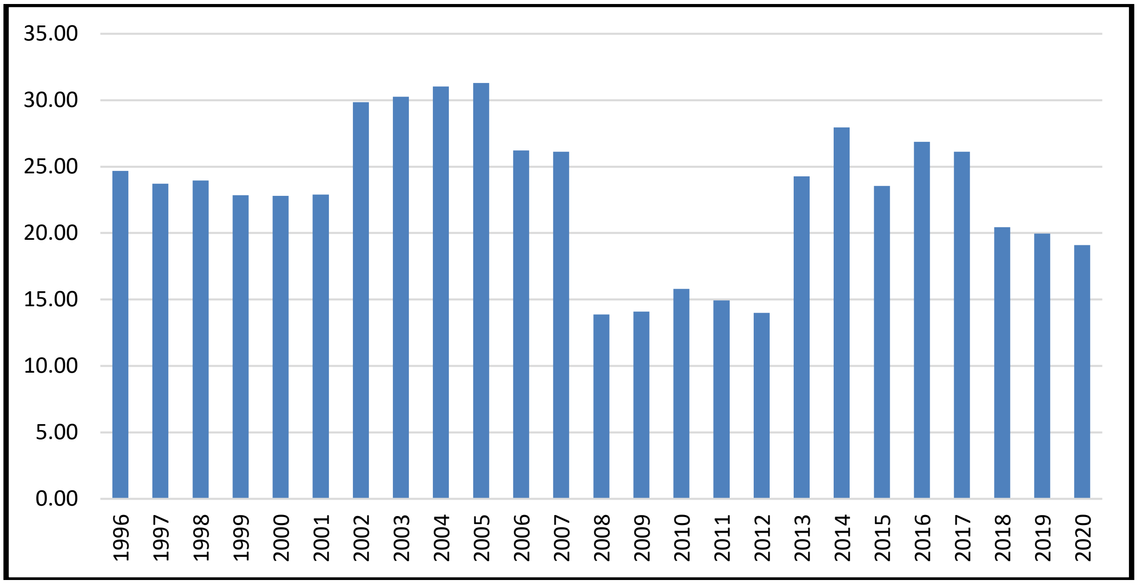
[21] The second crop share was 5.3 million ha in 2020

Figure 15: Average farm income gain from GM HT soybeans in Argentina 1996-2020 ($/ha)



Sources and notes:

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 typical weed control practices, 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. Additional information is available in Appendix 2
4. 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)
5. From 2013/14, second generation GM soybeans (tolerant to glyphosate and insect resistant) soybeans became available. The area planted to single trait (GM HT) soybeans has therefore subsequently declined as increasing numbers of farmers plant the stacked (HT and IR) soybeans

3.1.1.3 Brazil

GM HT soybeans were probably first planted in Brazil in 1997. Since then, the area planted has increased to 96% of the total crop in 2020[22].

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 2020 (Table 5). The net cost saving after deduction of the technology fee (assumed to be $8.8/ha in 2020) has been between $9/ha and $44/ha in recent years. At a national level, the adoption of GM HT soybeans increased farm income levels by $424.4 million in 2020. Cumulatively over the period 1997 to 2020, farm incomes have risen by $9.08 billion (in nominal terms).

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[22] Until 2003 all plantings were technically illegal

Table 5: Farm level income impact of using GM HT soybeans in Brazil 1997-2020

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
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	364.6
2016	40.05	32.60	502.2
2017	42.48	38.30	603.2
2018	42.04	33.28	444.5
2019	39.88	31.12	390.9
2020	41.44	32.68	424.4

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), Kleffmann herbicide usage data and own analysis
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
4. From 2013/14, second generation GM soybeans (tolerant to glyphosate and insect resistant) soybeans became available. The area planted to single trait (GM HT) soybeans has therefore subsequently declined as increasing numbers of farmers plant the stacked (HT and IR) soybeans

3.1.1.4 Paraguay and Uruguay

GM HT soybeans have been grown since 1999 and 2000 respectively in Paraguay and Uruguay. In 2020, they accounted for 98% of total soybean plantings in both countries[23]. Using the original farm level impact data derived from Argentine research (on conventional alternatives) and

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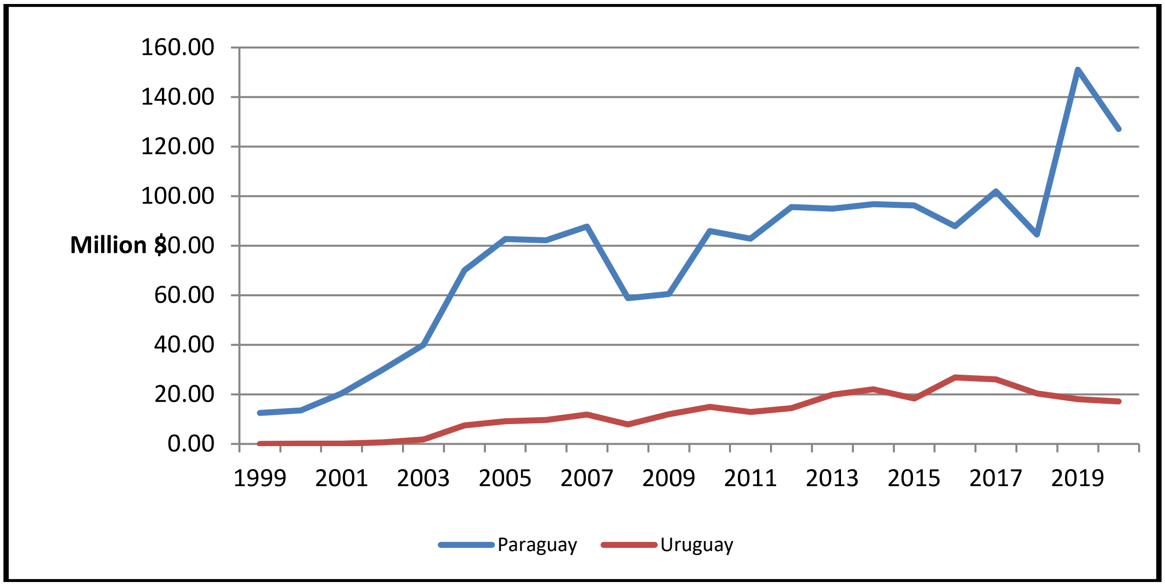
[23] As in Argentina, the majority of plantings are to farm saved or uncertified seed

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 (sources AMIS Global/Kleffmann)[24], Figure 16 summarises the national farm level income benefits that have been derived from using the technology.

In 2020, the respective national farm income gains were $27 million in Paraguay ($127.1 million including second crop benefits) and $17.1 million in Uruguay. Cumulatively, the farm income gains for the period 1999-2020 have been $1.66 billion in Paraguay and $271.8 million in Uruguay.

Figure 16: National farm income benefit from using GM HT soybeans in Paraguay and Uruguay 1999-2020 (million $)



Note: First year of adoption: Paraguay 1999, Uruguay 2000

3.1.1.5 Canada

First generation GM HT soybeans

GM HT soybeans were first planted in Canada in 1997. In 2020, the share of total plantings accounted for by first generation GM HT soybeans was 7% (0.14 million ha).

At the farm level, the main impacts of use have been similar to the impacts in the US. The average reduction in weed control costs has been within a range of $42/ha and $80/ha and the average farm income benefit (after deduction for the extra cost of the seed technology) has been within a range of $14/ha-$41/ha (Figure 17).

At the national level, the increase in farm income was $4.3 million in 2020 and since 1997, the cumulative increase in farm income has been $232.3 million (in nominal terms).

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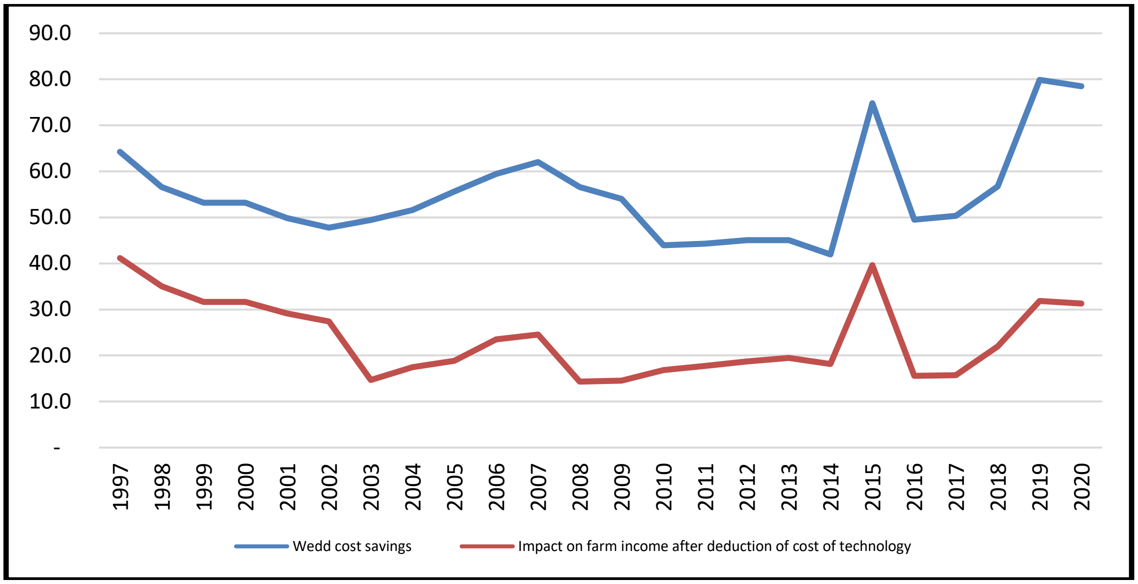
[24] Qaim & Traxler (2002 & 2005). The authors are not aware of any specific impact research having been conducted and published in Paraguay or Uruguay. Cost of herbicide data for recent years has been updated to reflect price and weed control practice changes in these countries (source: based on AMIS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

Figure 17: Farm level income impact of using GM HT soybeans (first generation) in Canada 1997-2020 ($/ha)



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. Original 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 1.62 million ha in 2020, equal to 79% 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 +$132.3/ha in 2020, with an aggregate increase in farm income of +$213.8 million. Since 2009, the total farm income gain has been $1.3 billion.

3.1.1.6 South Africa

The first year GM HT soybeans were planted commercially in South Africa was 2001. In 2020, 786,000 hectares (95%) of total soybean plantings were to varieties containing the GM HT trait. In terms of impact at the farm level, the average reduction in weed control costs has been within a range of $9/ha and $36/ha. After deduction of the cost of the technology, the average farm income gain has been within a range of 40.5/ha and £13/ha (Figure 18). At the national level, the increase in farm income was $11.3 million in 2020. Cumulatively the farm income gain since 2001 has been $68.3 million[25].

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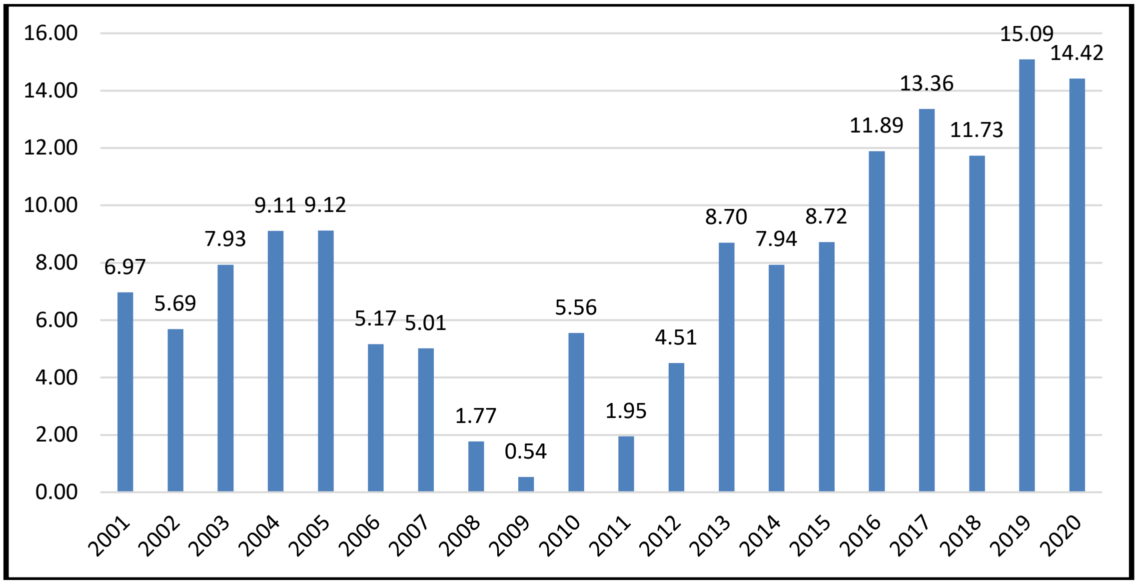
[25] This possibly understates the beneficial impact because it does not take into consideration any savings from reduced labour for hand weeding for some farms

Figure 18: Farm level income impact of using GM HT soybeans in South Africa 2001-2020 ($/ha)



Sources and notes:

1. Impact data, based on Kleffmann herbicide usage data, own analysis, Gouse (2014) and 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. The average cost of the technology in South Africa is very low (on a per hectare basis) at no more than $2-$3/ha. This reflects the high level of farm-saved seed typically used ((80%-85% of the crop) on which no seed premium (for the technology) is payable

3.1.1.7 Romania

Farmers in Romania have not been permitted to plant GM HT soybeans since the country 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%[26] have been recorded. This yield gain has arisen from the substantial improvements in weed control[27]. In recent years, as fields have been

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[26] Source: Brookes (2005)

[27] 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)

cleaned of problem weeds, the average yield gains have decreased and were reported at +13% in 2006[28];

- 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 obtained[29]) and cost savings derived;
- The average net increase in gross margin in 2006 was $59/ha (an average of $104/ha over the eight years of commercial use: Table 6);
- 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 production[30] (the annual average increase in production over the eight years was equal to 10.1%).

Table 6: 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

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[28] Source: Farmer survey conducted in 2006 on behalf of Monsanto Romania

[29] 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

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

3.1.1.8 Mexico

GM HT soybeans were first planted commercially in Mexico in 1997 on a trial basis and were allowed 'unrestricted' from 2012. However, adoption levels have typically remained below 10% of the total crop and 2016 was the last year when GM HT soybeans were planted (2,810 ha - out of total plantings of 211,000 ha). Since 2016 there have been no plantings, due to the permission for planting having been revoked by the Mexican regulatory authorities. Therefore, the impact analysis presented below relates to the period to 2016.

The main impacts of use derived from a combination of yield increase (a range of +2% to +13%, varying on a yearly basis) from better weed control and (herbicide) cost savings. However, as the GM HT trait was only made available in a limited number of varieties, and, more importantly, it was not available in leading/latest varieties, the average yield of the varieties containing the GM HT trait have tended to lag behind the yields obtained from the leading varieties (despite improvements in weed control) since 2014 (the recorded average yield difference between the GM HT soybeans and conventional alternatives has been between -1% and -2% post 2014). As a result, the average farm income impact over the period of all adoption (inclusive of the pilot planting years from 2004) has been within a range of -$3/ha in the most recent years of adoption to +$89/ha in the early years of adoption when positive yield gains and weed control cost savings were obtainable. In 2016, the last year of adoption, the net income effect was marginally positive (+$6/ha), as the cost savings associated with lower weed control with the GM HT soybeans were marginally higher than the revenue loss from a lower average yield of -1.8% (Table 7).

Table 7: Farm level income impact of using GM HT soybeans in Mexico 2004-2016

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
2016	22.61	5.96	0.02

Sources and notes:

1. Impact data based on Monsanto, 2005, 2007, 2008, 2009, 2010, 2013, 2014, 2015, 2016. 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 2014-2016 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

3.1.1.9 Bolivia

GM HT soybeans were officially permitted for planting in 2009, although 'illegal' plantings had occurred for several years beforehand. 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 2020, 1.35 million ha (97% of total crop) used GM HT technology.

The main impacts of the technology[31] have been (Table 8):

- 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 2020;
- 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;
- In 2020, the average farm income gain from using GM HT soybeans was $28.6/ha, resulting in a total farm income gain of $38.6 million. Cumulatively since 2005, the total farm income gain is estimated at $957.1 million.

Table 8: Farm level income impact of using GM HT soybeans in Bolivia 2005-2020

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
2012	109.60	105.22
2013	102.75	93.81
2014	101.01	107.31
2015	84.08	86.09
2016	52.11	53.58
2017	42.05	53.56
2018	35.14	44.76
2019	33.80	44.59
2020	28.62	38.59

Sources and notes:

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

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[31] Based on Fernandez et al (2009)

3.1.1.10 Summary of global economic impact

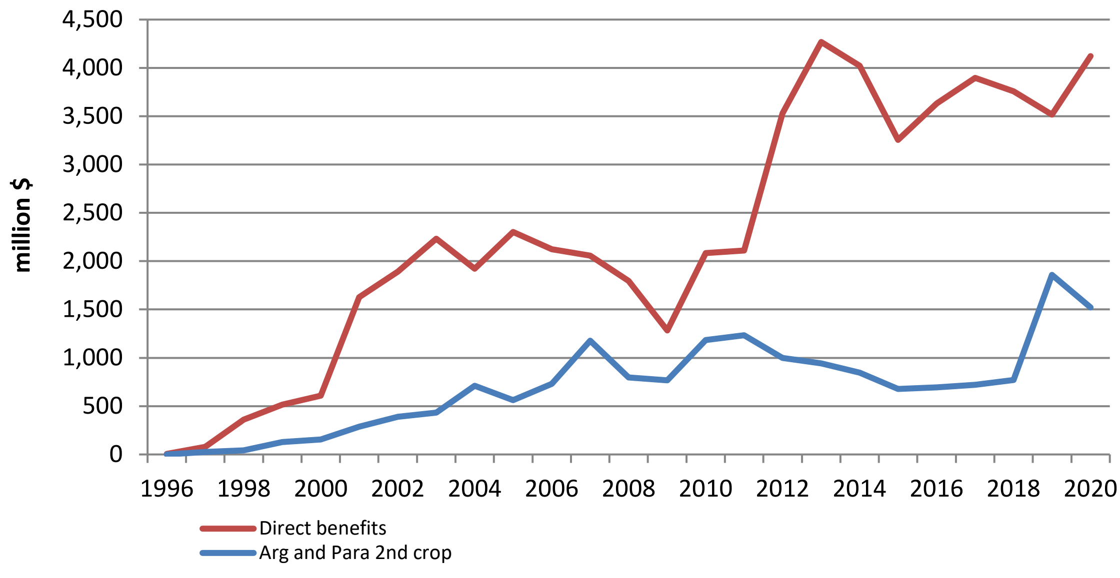
In global terms, the farm level impact of using GM HT technology in soybeans (excluding Intacta: see section 3.1.2) was $4.12 billion in 2020 (Figure 19). If the second crop benefits arising in Argentina are included the total is $5.64 billion. Cumulatively since 1996, the farm income benefit has been (in nominal terms) $57 billion ($74.65 billion if second crop gains in Argentina and Paraguay are included).

In terms of the total value of global soybean production in 2020, the additional farm income (inclusive of Argentine second crop gains) generated by the technology is equal to a value-added equivalent of 5.6%.

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).

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, $43 billion (58%) is due to yield gains/second crop benefits and the balance, 42%, is due to cost savings.

Figure 19: Global farm level income benefits derived from using GM HT soybeans 1996-2020 (million $)



3.1.2 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 over the eight-year period to 2020-21 is shown in Table 9. The total farm income gain recorded on a cumulative total usage area of 155.8 million ha was $16.05 billion.

Table 9: Main impacts of insect resistant soybeans 2013/14 to 2020/21

	Cumulative area planted ('000 ha)	Average yield gain (%)	Average cost of technology (seed premium) ($/ha)	Average farm income gain ($/ha)	Aggregate farm income gain (million $)
Brazil	123,141	+9.4	36.84	107.20	13,200.7
Argentina	20,869	+7.2	26.25	73.56	1,535.0
Paraguay	9,454	+13.4	37.22	121.39	1,147.6
Uruguay	2,367	+7.3	29.63	70.68	167.3
Total		**9.3**			**16,050**

Notes:

1. Impact data based on pre-commercial trials in 2011 and 2013 and post production farm surveys (post market monitoring: Monsanto/Bayer)
2. Impact on cost of production includes herbicide cost savings, as indicated in section 3.1.1 for first generation HT soybeans plus insecticide use savings of about $12/ha in Brazil, $11/ha in Argentina, $40/ha in Paraguay and $14/ha in Uruguay

3.1.3 Herbicide tolerant maize

3.1.3.1 The US

Herbicide tolerant maize[32] has been used commercially in the US since 1997 and in 2020 was planted on 89% of the total US maize crop. The impact of using this technology at the farm level is summarised in Figure 20. As with herbicide tolerant soybeans, the main benefit has been to reduce costs, and hence improve profitability levels. The average cost of the technology (seed premium over the period 1996-2020 has been $24.38/ha ($24.82/ha in 2020) and the average weed control cost savings equal to $56.98/ha ($57.48/ha in 2020). Average profitability has therefore improved by $30.98/ha over the 1996-2020 period ($32.61/ha in 2020). The net gain to farm income in 2020 was $968.4 million and cumulatively, since 1997, the farm income benefit has been $12.74 billion.

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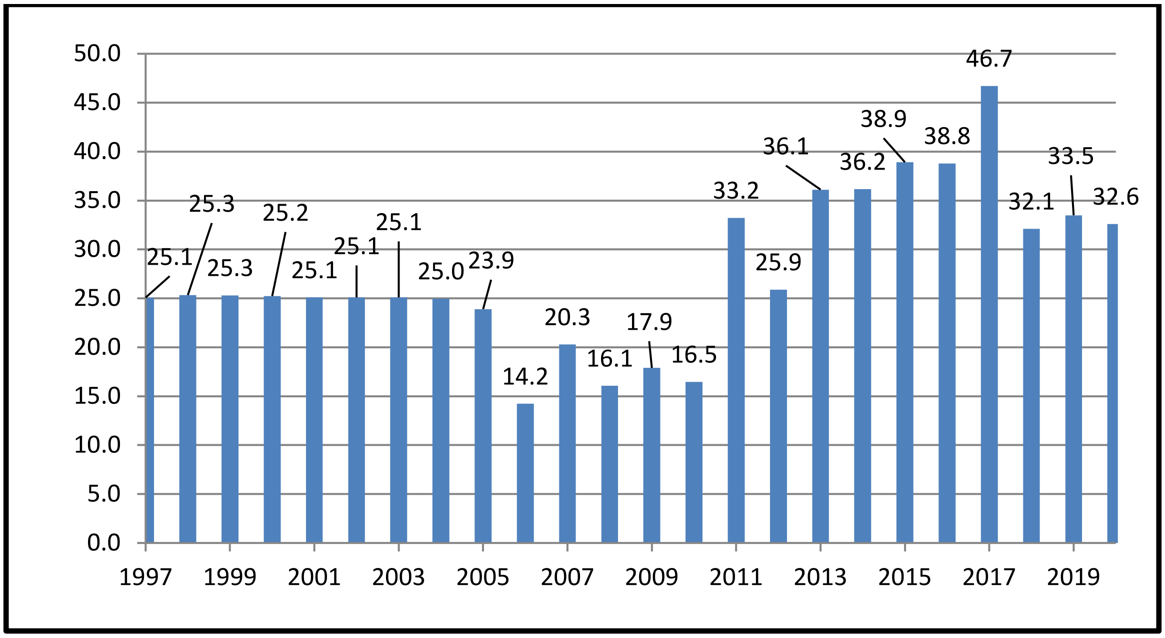
[32] Tolerant to glufosinate ammonium or to glyphosate (or both herbicides), although cultivars tolerant to glyphosate have accounted for the majority of plantings. Also, corn varieties tolerant to these two herbicides plus tolerance to 2 4 D from 2017

Figure 20: Farm income impact of using GM HT maize in the US 1997-2020 ($/ha)

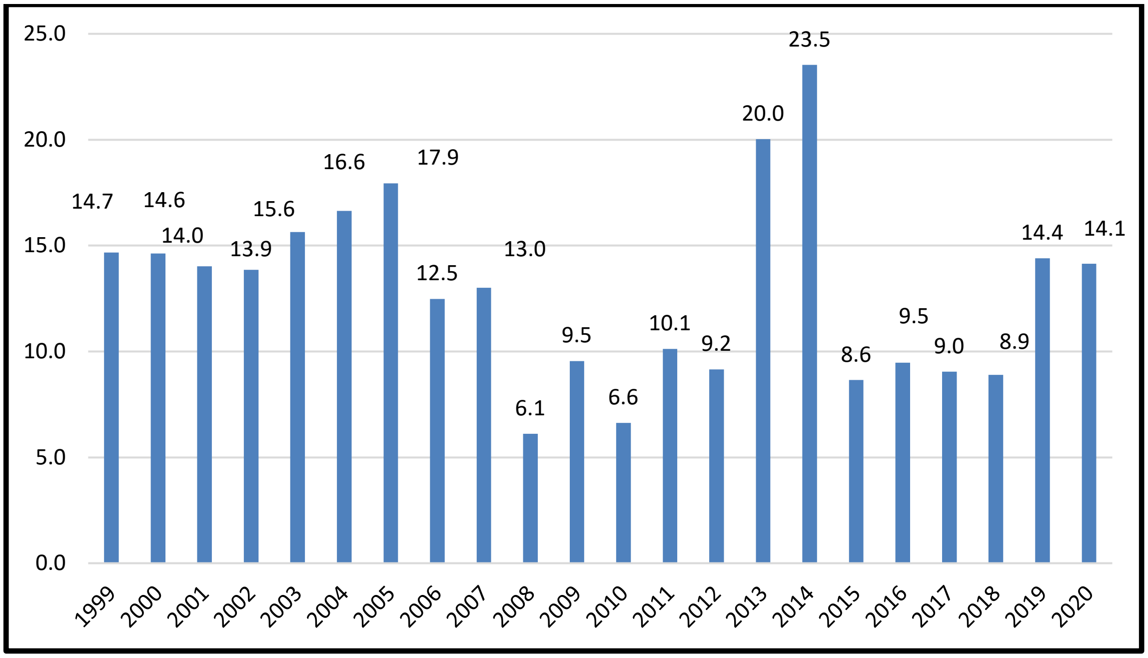


Source and notes: Impact analysis based on Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006), Johnson & Strom (2008) and updated from 2008 to reflect changes in herbicide prices and typical weed control programmes

3.1.3.2 Canada

In Canada, GM HT maize was first planted commercially in 1999. In 2020, the proportion of total plantings accounted for by varieties containing a GM HT trait was 98%. As in the US, the main benefit has been to reduce costs and to improve profitability levels (Figure 21). Average annual profitability has improved by $12.4/ha over the period 1999-2020, based on weed control savings of $42/ha less the average additional cost of the technology over this period of $29.69/ha. In 2020, the average farm income gain was $14.1/ha (seed premium $31.61/ha) resulting in an aggregate increase in farm income of $19.4 million. Since 1999 the farm income benefit has been $225.4 million.

Figure 21: Farm level income impact of using GM HT maize in Canada 1999-2020 ($/ha)



Source and notes: Impact analysis based on data from Ontario Ministry of Agriculture, Kleffmann/Kynetec herbicide usage data and Monsanto/Bayer Canada

3.1.3.3 Argentina

GM HT maize was first planted commercially in Argentina in 2004, and in 2020, varieties containing a GM HT trait were planted on 6.27 million ha (98% 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'. Initially the HT trait was available as a single trait in seed only and there was limited take up until stacked traited seed, containing both the HT and IR trait became available in 2007. Following this there was more rapid adoption, so that in 2020, when 92% of the total crop used varieties containing an HT trait, 96% of this seed was stacked seed.

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 average cost of the technology has been $16.8/ha over the period 2004-2020;
- 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;
- The average farm income gain arising from the combination of higher yields and reduced weed control costs, for the 2004-2020 period has been $97.48/ha;

- In 2020, the additional farm income at a national level, from using single traited GM HT technology, was +$35.4 million, and cumulatively since 2004, the income gain has been $443.1 million.

Stacked-traited GM HT seed

- The average yield gain identified since adoption has been +15.75%[33]. Given the average yield impact identified for the early years of adoption of the single traited GM IR maize was +5.5% (see section 3.2.7), our analysis has applied this level of impact to the GM IR component of the study (section 3.2.7), 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 average cost of the technology (seed premium) applied to GM HT component for the period 2007-2020 has been $18/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 2020 was +$102.37/ha, giving an aggregated national level farm income gain of $551.7 million. Cumulatively since 2007, the farm income gain has been $4.56 billion.

3.1.3.4 South Africa

Herbicide tolerant maize has been grown commercially in South Africa since 2003, and in 2020, 2.16 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), with the average net farm income gain for the period 2003 to 2020 having been $5/ha (based on an average cost of technology of $13.5/ha and an average wed control cost reduction of $18.5/ha. In 2020, the net farm income gain was +$1/ha. At the national level, this is equivalent to a net gain of $2.44 million in 2020 and since 2003, the cumulative income gain has been $102.6 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. It should also 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.

3.1.3.5 Philippines

GM HT maize was first grown commercially in 2006, and in 2020 was planted on 686,000 hectares. The technology has provided higher yields from improved weed control compared to conventionally grown maize using a combination of herbicides and/or hand weeding methods. In the first two years of adoption, (based on industry sources) this was estimated to be +15% for the limited number of early adopters. A more detailed analysis by Gonsales et al (2009) drawn from a larger ‘population’ of adopters, identified an average yield gain of +5%. Over the period 2006-2020, the average cost of the technology (seed premium) has been $39.1/ha ($40.2/ha in 2020), which compared to the average reduction in weed control costs of $29.75/ha, resulted in a

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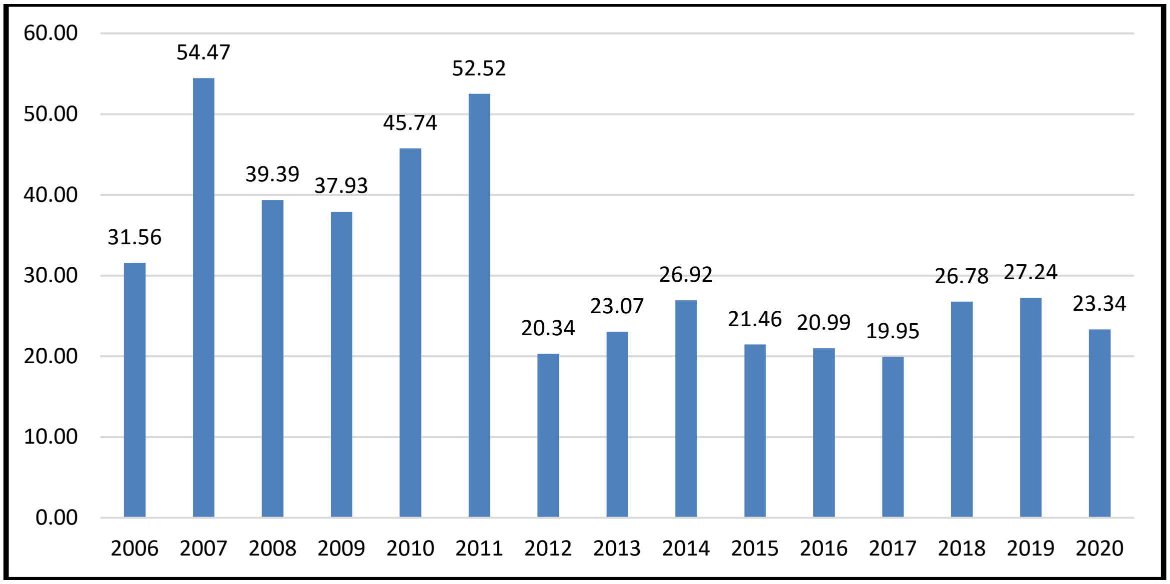
[33] Based on farm level feedback/surveys to the technology providers

net increase in total costs of production of about $9.35/ha[34]. Nevertheless, the average impact on income has been +$28.9/ha due to the higher yields. In 2020, the average net farm income gain from using GM HT maize was +$23.34/ha (Figure 22), which at the national level was equal to +$16 million. Cumulatively, since 2006, the total farm income gain has been $237.9 million.

Figure 22: Farm level income impact of using GM HT maize in Philippines 2006-2020 ($/ha)



Source and notes: Impact analysis based on data from Gonsales et al (2009), Kleffmann herbicide usage data and Monsanto/Bayer Philippines

3.1.3.6 Brazil

2020 was the eleventh year in which GM HT maize was planted in Brazil (on 83% of the total crop: 16.5 million ha). The technology is estimated to have delivered an average yield gain from improved weed control of 3.5%. The average cost of production has decreased marginally (by $2.5/ha), as the cost of the technology (seed premium: $22.92/ha) has been marginally higher than the savings from lower weed control costs of $16.9/ha). In net farm income terms, inclusive of yield gain, the average farm income gain has been $21.6/ha. At the national level, the cumulative farm income gain has been $2.3 billion (2009-2020).

3.1.3.7 Colombia

GM HT maize was first planted in Colombia in 2009 and in 2020, 109,000 ha (58% of the commercial total crop) used this technology (in the form of stacked traited seed, with GM IR technology).

Analysis of its impact is drawn from Brookes (2020), which also draws on a study by Mendez et al (2011) and surveys of maize growers in 2015 and 2017 by Celeres. These analyses examined the impact for the stacked traited seed but for the purposes of this analysis of the HT trait, all of the positive yield impact has been assumed to be attributed to the IR trait (presented in section 3.2.1.8 below).

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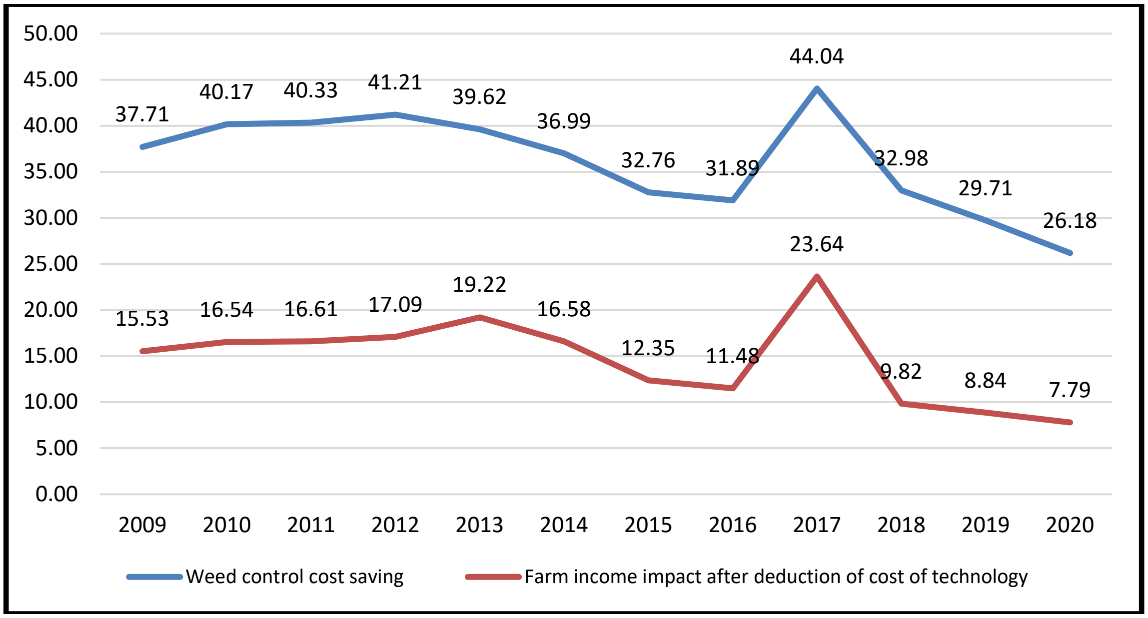
[34] Based on own analysis of industry data and Kleffmann/AMIS Global pesticide usage data

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 $7.8/ha in 2020 (seed premium of $18.4/ha, counterbalanced by weed control cost savings of $26.2/ha: Figure 23). At the national level, the average farm income gain for the period 2009-2020 has been $13.85/ha (average seed premium of $20.88/ha, counterbalanced by weed control cost savings of $34.73/ha). The aggregate total income gain in 2020 was $0.85 million, with the cumulative gain since 2009 having been $11.18 million.

Figure 23: Farm level income impact of using GM HT maize in Colombia 2009-2020 ($/ha)



Sources: Derived from Brookes (2020), Mendez et al (2011) and Celeres 2015, 2017

3.1.3.8 Uruguay

Maize farmers in Uruguay gained access to GM HT maize technology in 2011 (via stacked traited seed) and 90% of the country's 143,000 ha crop used this technology in 2020. 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 that if only cost of production changes are assumed (all yield gains are associated with better pest control and none attributed to improved weed control), then the average seed premium for this technology of $16.17/ha is greater than the average weed control saving of $13.37/ha, resulting in a net loss of $2.8/ha. This is equal to a net loss of about $2.5 million at the national level since 2011. However, all of the GM maize seed used by farmers is stacked containing the insect resistant and herbicide tolerant traits and has delivered an average yield gain of +5.5%. Taken in this context, the use of the technology will have delivered overall improvements in farm income and for quantification of this, readers should refer to section 3.2.10 for further information on the performance of the insect resistant maize traited seed.

3.1.3.9 Paraguay

GM HT technology was used for the first time in 2013 in Paraguay, and in 2020, 66% of the country's maize crop (471,740 ha) used seed containing this trait. Based on an average seed premium of $13.9/ha (source: industry) and an estimated average herbicide cost saving of

$15.3/ha (sources: industry and AMIS Global 2013 and 2015), the average farm income gain has been $2.4/ha (2020 $3.4/ha). At the national level, this was equal to about $0.17 million in 2020 and a cumulative gain of $7.32 million since 2013.

3.1.3.10 Vietnam

GM HT maize was first planted commercially in 2015, and in 2020 was planted on 92,000 ha (9.7% of the total crop). Analysis by Brookes (2017), shows that a yield gain of over 12% has been identified from the 2015 (first year) trials of the stacked (HT and IR) maize. Further analysis by Brookes and Dinh (2021) identified an average yield gain for the stacked traited seed of +15.22%. In this analysis we have assumed that 5% of this yield gain has arisen from improved weed control (the remaining 10.22% yield gain attributed to the insect pest resistance trait), coupled with an attributed cost of (HT) technology of $17.12/ha, the average farm income gain over the six years of adoption has been $72.81/ha. At the national level, this equates to an aggregate net farm income gain of $23.04 million (2015-2020).

3.1.3.11 Summary of global economic impact

In global terms, the farm level economic impact of using GM HT technology in maize was $1.55 billion in 2020 (62% of which was in the US). Cumulatively since 1997, the farm income benefit has been (in nominal terms) $20.2 billion. Of this, 61% has been due to cost savings and 39% 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 1.2% of global maize production.

3.1.4 Herbicide tolerant cotton

3.1.4.1 The US

GM HT cotton was first grown commercially in the US in 1997 and in 2020 was planted on 91% of total cotton plantings[35]. The farm income impact of using GM HT cotton is summarised in Figure 24. The primary benefit has been to reduce weed control costs, and hence improve profitability levels. Over the period to 2020, the average farm income gain has been $16.2/ha. In 2020, the net income gain was $6.1/ha. Overall, the aggregate net direct farm income impact in 2020 was $19 million (this does not take into consideration any non-pecuniary benefits associated with adoption of the technology: see section 3.4). Cumulatively since 1997 there has been a net farm income benefit from using the technology of $1.17 billion.

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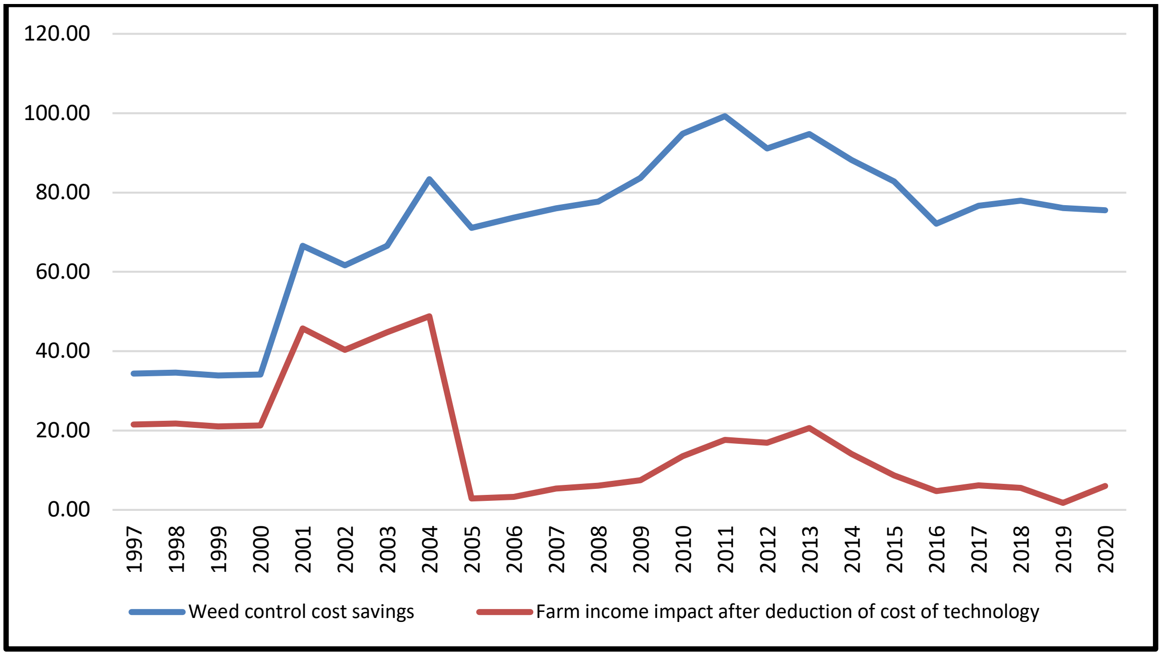
[35] Although there have been GM HT cultivars tolerant to glyphosate and glufosinate, glyphosate tolerant cultivars have dominated

Figure 24: Farm level income impact of using GM HT cotton in the US 1997-2020 ($/ha)



Source and notes:

1. Early years analysis based on Carpenter & Gianessi (2002), Sankala & Blumenthal (2003 & 2006) and Johnson & Strom (2008). Post 2008 based on own analysis using data from Kynetec, USDA and extension services
2. Average cost of technology 1997-2020: $58.1/ha. The significant decrease in net farm income gains post 2004 largely reflects the availability (and wide adoption) of second-generation HT cotton which was more expensive than the early traits.

3.1.4.2 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 2020, 100% (280,000 ha), 100% 16,175 ha), 100% (450,000 ha), 97% (145,500 ha), 56% (4,865 ha) and 81% (1,12,600 ha) respectively of the total Australian, South African, Argentine, 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, although in Colombia there is published research (Brookes (2020)) that draws on analysis of the impact of stacked-traited cotton (that combines IR and HT traits). 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 impact[36]. Our analysis

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

summarised below in Table 10 is primarily 'own analysis' that draws on the limited published analysis and industry source estimates[37]:

Table 10: Summary of cumulative farm level impact of using GM HT cotton: other countries:

Country	Average yield impact (%)	Average cost of technology ($/ha)	Average reduction in weed control costs before deduction of technology cost ($/ha)	Average impact on farm income ($/ha)	Aggregate farm income gain (million $)
Australia (2000-2020)	Nil	+62.53	-90.76	+28.23	+145.4
Argentina (2002-2020)	+1.6	+21.44	-26.12	+43.39	+238.4
South Africa (2001-2020)	Nil	+16.66	-48.61	+31.95	+8.31
Mexico (2006-2020)	+14	+51.42	-29.10	+297.51	+546.7
Colombia (2006-2020)	+3.5	+73.00	-90.43	+63.72	+18.89
Brazil (2009-2020)	+1.6	+30.83	-42.76	+53.15	+397.3

3.1.4.3 Summary of global economic impact

Across the seven countries using GM HT cotton in 2020, the total farm income impact derived from using GM HT cotton was +$134.8 million. Cumulatively since 1997, there have been net farm income gains of $2.53 billion. Of this, 58% has been due to cost savings and 42% to yield gains (from improved weed control relative to the level of weed control achieved using conventional technology).

3.1.5 Herbicide tolerant canola

3.1.5.1 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 2020 was 97% of the total crop (8.05 million ha of GM HT crop).

The farm level impact of using GM HT canola in Canada since 1996 is summarised in Figure 25. 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

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[37] Sources: Monsanto Australia, Argentina, South Africa & Mexico, including Annual reports by Monsanto to the Mexican government (as part of post market monitoring). Also, Kleffmann herbicide usage data in each country and analysis by Galvão (2010-2015) for Brazil

production of nearly 7%). In addition, a higher price 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 alternatives[38] 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 Figure 25 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 \$20/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 \$5/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 \$568.9 million in 2020. The cumulative farm income benefit over the 1996-2020 period (in nominal terms) was \$7.57 billion.

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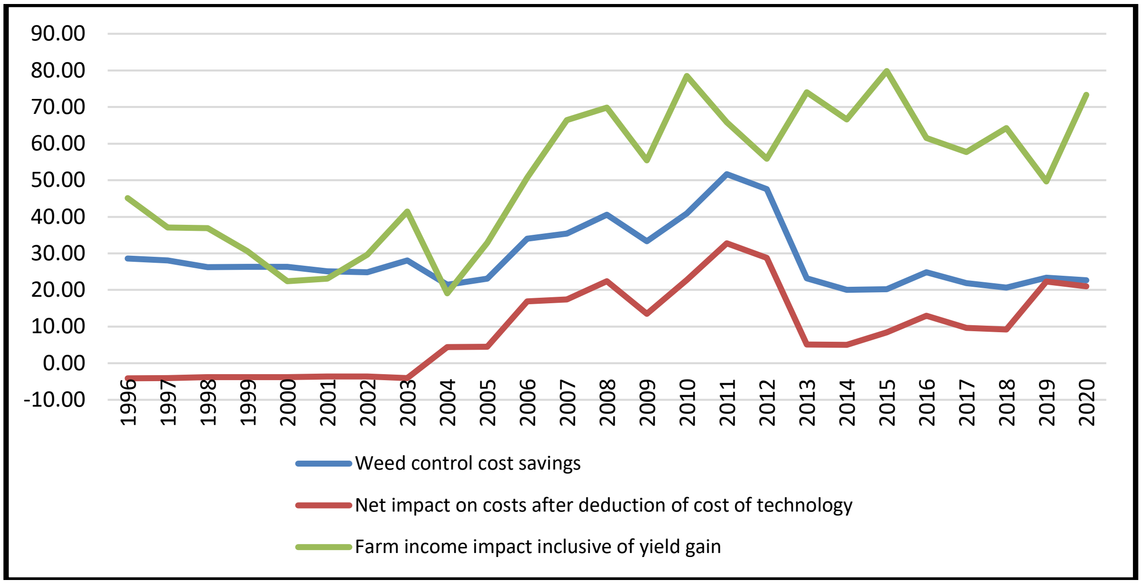
[38] The main one of which is 'Clearfield' conventionally derived herbicide tolerant varieties. Also, hybrid canola now accounts for the majority of plantings (including some GM hybrids) with the hybrid vigour delivered by conventional breeding techniques (even in the GM HT (to glyphosate) varieties)

Figure 25: Farm level income impact of using GM HT canola in Canada 1996-2020 ($/ha)



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, +2.6% 2016, +2.5% 2017, +2.9% 2018, +4.3% 2019 and +2% 2020. 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, +7.3% 2016, +7.5% 2017, +9.5% 2018, +2.6% 2019 and +7.4% 2020
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
4. Values presented are the weighted average changes – with weighting based on the proportion of the crop area planted to seed containing either glyphosate or glufosinate tolerant varieties

3.1.5.2 The US

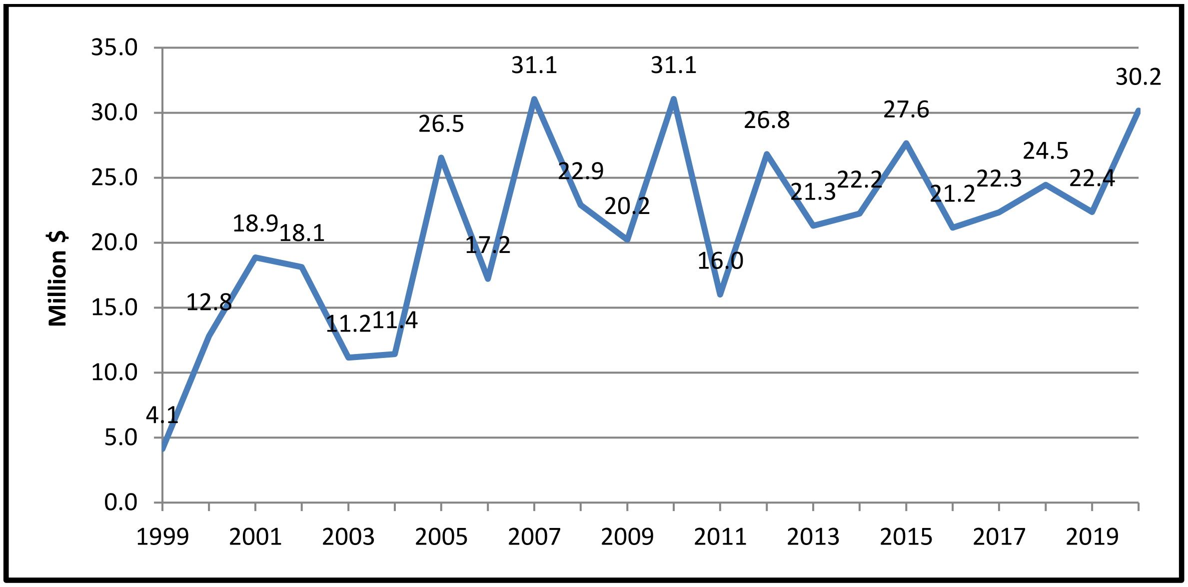
GM HT canola has been planted on a commercial basis in the US since 1999. In 2020, 95% of the US canola crop was GM HT (688,230 ha).

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 3.1.5.1) 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');

- 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 ($11.2/ha in 2020) for glufosinate tolerant canola and $19-$79/ha for glyphosate tolerant canola ($24/ha 2020);
- The net impact on gross margins has been between +$22/ha and +$90/ha ($50.55/ha in 2020) for glufosinate tolerant canola, and between +$23/ha and +$61/ha for glyphosate tolerant canola ($21.54/ha in 2020);
- At the national level the total farm income benefit in 2020 was $30.2 million (Figure 26) and the cumulative benefit since 1999 has been $460 million.

Figure 26: National farm income impact: GM HT canola in the US 1999-2020 (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 3.1.5.1

3.1.5.3 Australia

GM HT canola was first planted for commercial use in 2008. In 2020, GM HT canola was planted on 562,500 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 11, 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 have 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 $38.2/ha and a total farm income gain of $25.1 million in 2020 (Table 11). Cumulatively since 2008, the total farm income gain has been $156.8 million.

It is noted that the share of GM HT canola has risen to only 25% 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 11: Farm level income impact of using GM HT canola in Australia 2008-2020 ($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	17,193
2016	8.69	-0.97	34.66	15,516
2017	8.96	-1.0	28.29	13,907
2018	8.74	-0.98	27.14	13,538
2019	8.13	-0.91	26.15	14,907
2020	7.97	-0.89	44.55	25,562

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, +8% 2016-20. 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 premium 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 premium of 7%, the net impact on price was to apply a price discount of -2.9%. Since 2012, the price discount applied is -2%

3.1.5.4 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 $624.1 million in 2020. Cumulatively since 1996, the farm income benefit has been (in nominal terms) $8.18 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 2020, the additional farm income generated by the technology is equal to a value-added equivalent of 5.9%. Relative to the value of global canola production in 2020, the farm income benefit added the equivalent of 1.8%.

3.1.6 GM herbicide tolerant (GM HT) sugar beet

3.1.6.1 US

GM HT sugar beet was first grown commercially in the US in 2007. In 2020, 462,280 hectares of GM HT sugar beet were planted, equal to all of the 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/ha[39]), 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 3.4, estimated in the maize, 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 (Figure 27) 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 2020 of $73.6 million to US sugar beet farmers (average gain per hectare of $129.6/ha). Cumulatively, the farm income gain, since 2007 has been $733.4 million.

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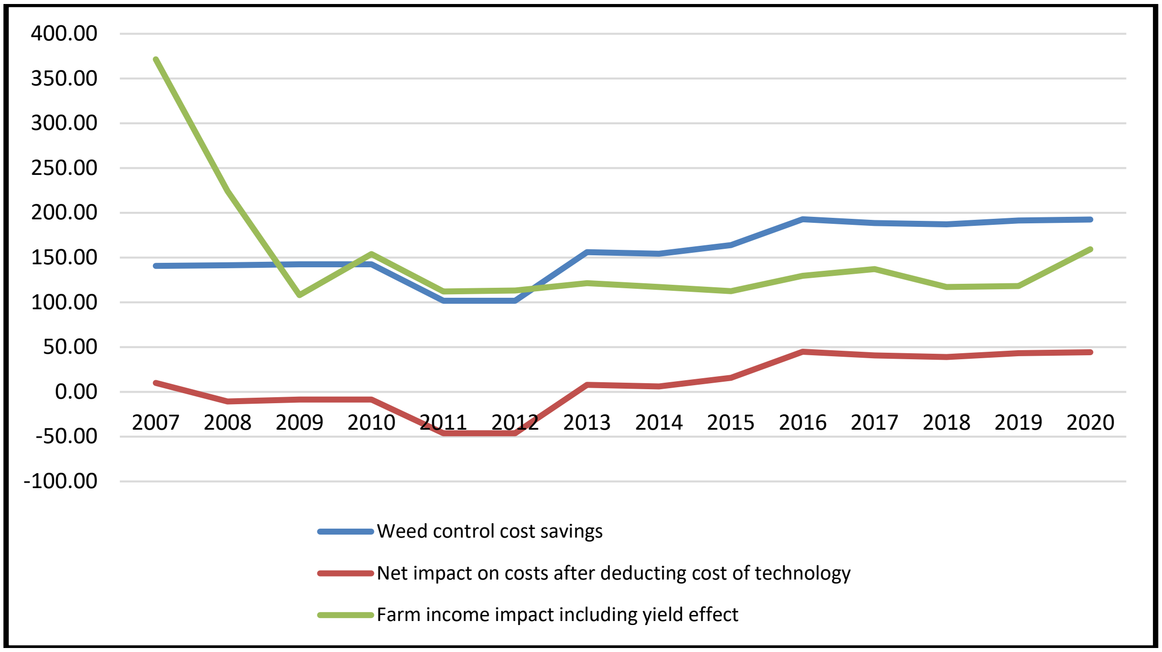
[39] Differences in the seed premium assumed by the different analysts reflect slightly different assumptions on seed rates used by farmers (the technology premium being charged per bag of seed)

Figure 27: Farm level income impact of using GM HT sugar beet in the US 2007-2020 ($/ha)



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

Notes:

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 +3.4% (2008-2020)
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 has been used for subsequent years

3.1.6.2 Canada

GM HT sugar beet has also been used in the small Canadian sugar beet sector since 2008. In 2020, all of crop of 17,400 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 2020 was $3.7 million and cumulatively since 2008, the income gain has been $21.9 million.

3.2 Insect resistant crops

3.2.1 GM insect resistant[40] (GM IR) maize

3.2.1.1 US

GM IR maize was first planted in the US in 1996 and in 2020 seed containing GM IR traits was planted on 82% (27.37 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 Figure 28:

- 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 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 latter analysis has been used as the basis for our analysis below;
- 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 technology[41], the net impact on costs has been an increase of $7/ha to $27/ha;
- The annual total national farm income benefit from using the technology has risen from $13.54 million in 1996 to $1.93 billion in 2020. The cumulative farm income benefit over the 1996-2020 period (in nominal terms) was $34.3 billion;
- The average net farm income gain over the period 1996-2020 has been +$81.5/ha.

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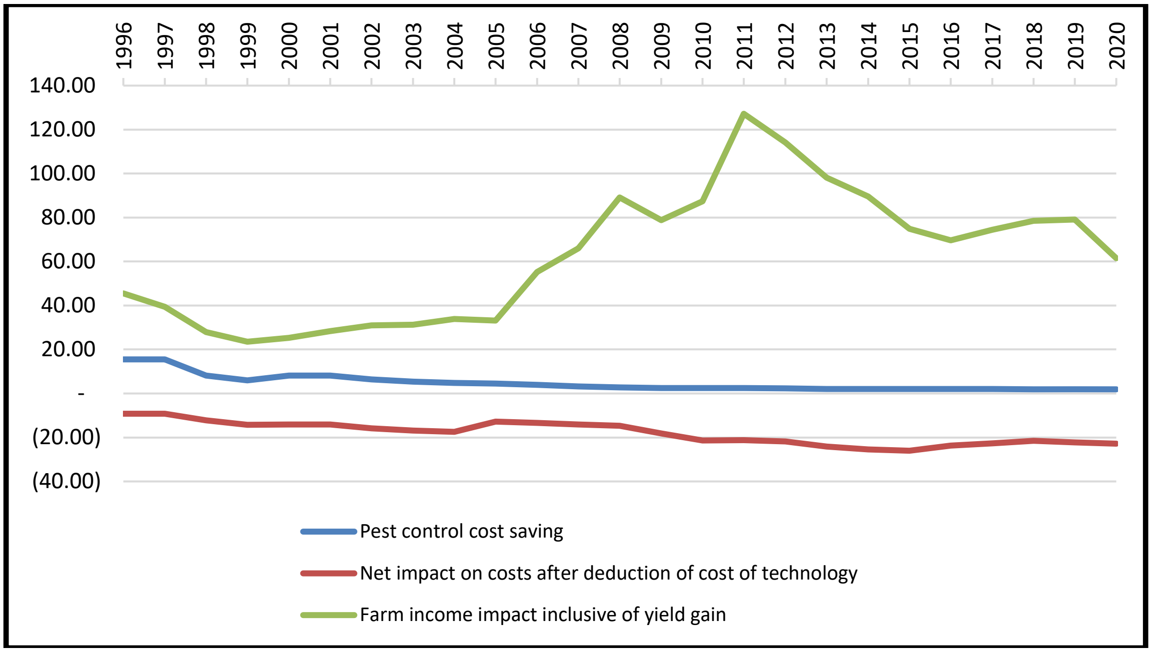
[40] The first generation being resistant to stalk boring pests but later generations including resistance against cutworms and earworms

[41] Which tends to be mostly purchased as stacked-traited seed – for this aspect of technology the seed premium has been in the range of $25/ha to $30/ha in recent years compared to the 'lower $20s/ha 10-15 years ago

Figure 28: Farm level income impact of using GM IR maize in the US 1996-2020 ($/ha)



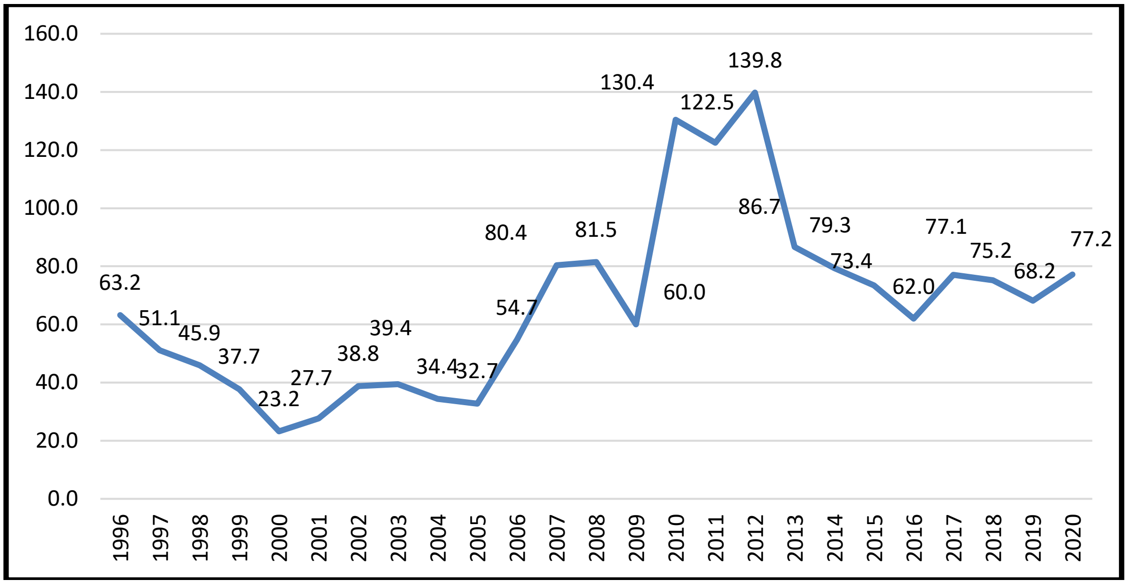
Sources and notes:

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

3.2.1.2 Canada

GM IR maize has also been grown commercially in Canada since 1996. In 2020, it accounted for 81% (1.14 million ha) of the total Canadian maize crop. The impact of this technology in Canada has been very similar to the impact in the US (similar yield and cost of production impacts). At the farm level this has resulted in net farm income gains (after deduction of the technology cost, pest control cost savings and yield gains) of between $24/ha and $140/ha (Figure 29). At the national level, this equates to additional farm income generated from the use of GM IR maize of $87.7 million in 2020 and cumulatively since 1996, additional farm income (in nominal terms) of $1.39 billion. On a per hectare basis, the average farm income benefit has been $74.92/ha (1997-2020).

Figure 29: Farm income impact: GM IR maize in Canada 1996-2020 ($/ha)



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

3.2.1.3 Argentina

In 2020, GM IR maize traits were planted on 93% (5.95 m ha) of the total Argentine maize crop (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. Subsequent (industry source) estimates provided to the authors put the average yield increase in the 2005-2015 period 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 because very few maize growers have traditionally used insecticides as a method of control for corn boring pests. Therefore, average costs of production increased by between $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 (IR part) technology relative to conventional seed has been in the range of $10/ha-$33/ha, with an average cost over the 1998-2020 period of $23.12/ha.

The net impact on farm profit margins (inclusive of the yield gain and after deduction of the technology cost) has been an increase of between $3/ha and $66/ha. In 2020, the national level impact on profitability was an increase of $204.2 million. Cumulatively, the farm income gain, since 1998 has been $1.9 billion.

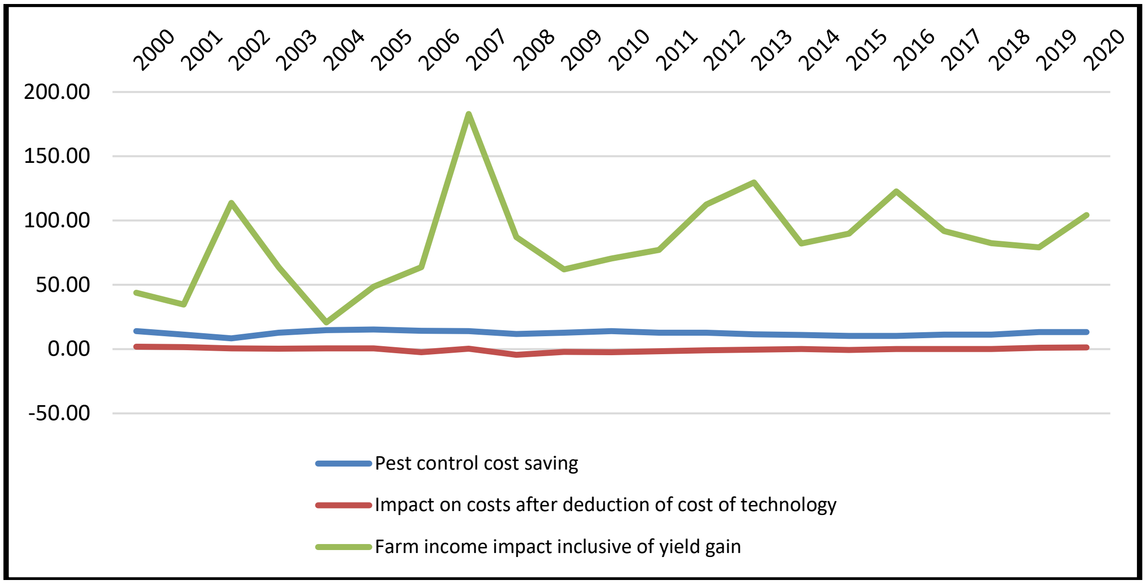
3.2.1.4 South Africa

GM IR maize has been grown commercially in South Africa since 2000. In 2020, 79% (2.07 million ha) of the country's total maize crop of 2.6 million ha used varieties containing GM IR technology.

The impact on farm profitability is summarised in Figure 30. 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%[42] (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, as shown in Figure 30. The average farm income gain after inclusion of yield gains was been in a range of $21/ha to $183/ha (average $93.6/ha 2000-2020)

At the national level, the increase in farm income in 2020 was $215.5 million and cumulatively since 2000 it has been $2.57 billion.

Figure 30: Farm level income impact of using GM IR maize in South Africa 2000-2020 ($/ha)



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

3.2.1.5 Spain

Spain has been commercially growing GM IR maize since 1998 and in 2020, 28% (98,150 ha) of the country's maize crop was planted to varieties containing a GM IR trait. As in the other countries

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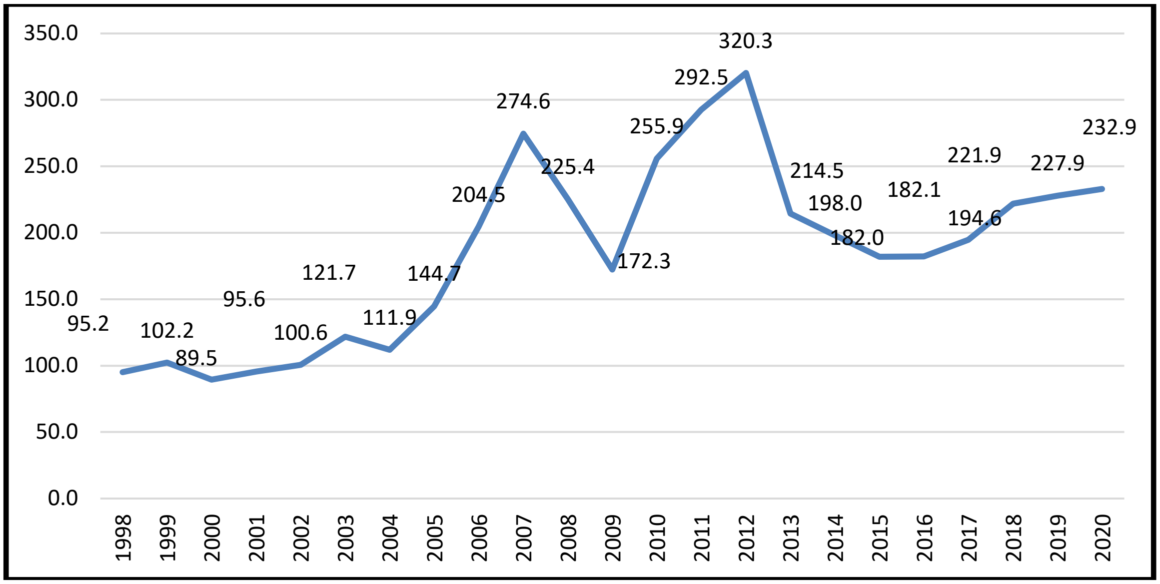
[42] Van der Weld (2009)

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%[43]. There has also been a net annual average saving on cost of production (from lower insecticide use) of between $37/ha and $61/ha[44] in the early years of adoption. This has been the basis of analysis to 2008. From 2009, the analysis draws on Riesgo et al (2012), as summarised in Brookes (2019). Over the period 1998-2020, the average coat of the technology has been$41.9/ha and the average farm income gain $209.6/ha (Figure 31). This income gain derives mostly from higher yields, with an average of about $20.7/ha coming from less expenditure on insecticides. At the national level, these yield gains and cost savings have resulted in higher farm income, which in 2020 was 22.9 million and cumulatively since 1998 the increase in farm income (in nominal terms) has been $371.9 million.

Figure 31: Farm level income impact of using GM IR maize in Spain 1998-2020 ($/ha)



Sources and notes:

1. Impact data (based on Brookes (2003), Brookes (2008), Brookes (2019) 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

3.2.1.6 Other EU countries

In 2020, the only other EU member state where GM IR maize was planted was Portugal (4,216 ha out of a total crop of 76,000 ha). A summary of the impact of GM IR technology in Portugal is presented in Table 12. This shows that in 2020, the additional farm income derived from using

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

[44] Source: Brookes (2003) and Alcade (1999)

GM IR technology was +$0.918 million, and cumulatively over the period 2005-2020, the total income gain was $14.7 million (an average of +$160/ha).

Table 12: Farm level income impact of using GM IR maize in Portugal 2020

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 $)
2005	4,216	+12.5	42.66	0	217.8	0.918

Source and notes:

1. Source: based on Brookes (2008)
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

3.2.1.7 Brazil

Brazil first used GM IR maize technology in 2008. In 2020, 18 million ha of GM IR maize were planted (91% of the total crop). Analysis from Galvao (2009-2015) and Kleffmann/Kynetec pesticide usage data has been used as the basis for estimating the aggregate impacts on farm income and is presented in Table 13. Over the period 2008-2020, the average yield gain has been +11.5%, the average cost of the technology $56/ha and the average farm income gain $53.7/ha. In 2020, the total income gain was $201.1 million, with the cumulative benefit since 2008 equal to $7.86 billion.

Table 13: Farm level income impact of using GM IR maize in Brazil 2008-2020

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	13.58	-41.44	40.33	499.36
2016	13.46	-41.08	62.93	936.43
2017	17.04	-33.46	29.58	404.63
2018	15.07	-42.10	29.67	413.88
2019	15.07	-42.1	34.69	563.66
2020	15.07	-42.1	11.14	202.00

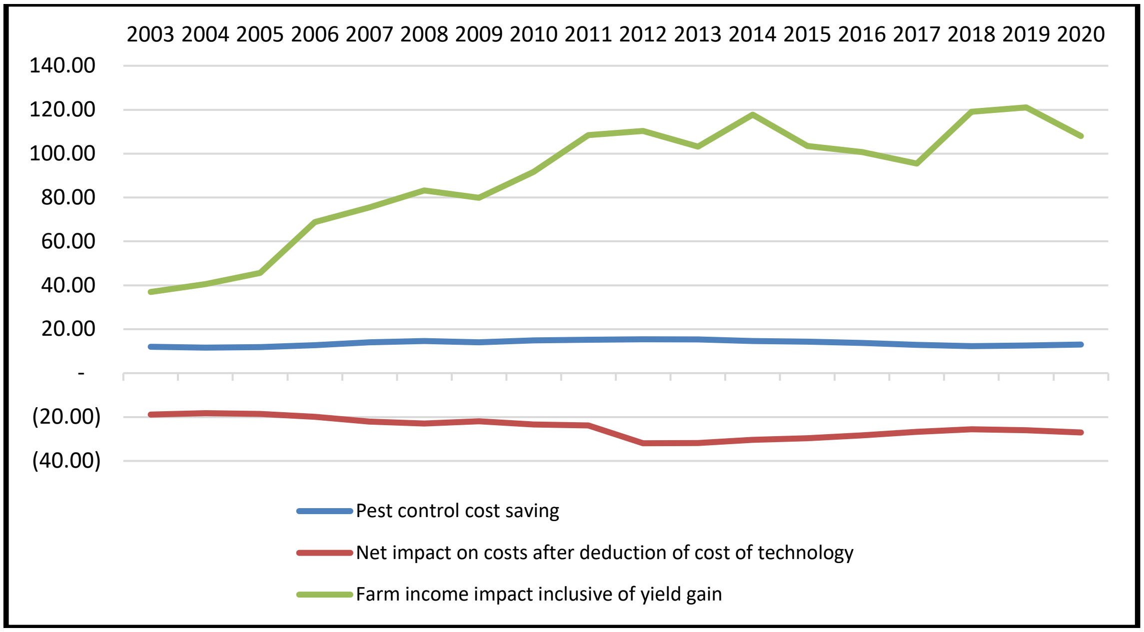
Sources and notes:

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

3.2.1.7 Philippines

GM IR maize has been grown commercially in Philippines since 2003. In 2020, 683,085 hectares out of total plantings of 2.57 million (27%) were to varieties containing GM IR technology. 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. From 2008, a yield impact of +18% has been used based on Gonsales et al (2009). Based on the findings of these research papers, there has been a small average annual insecticide cost saving of about $12/ha-$15/ha and with an average cost of the technology of $42/ha, the net impact on costs of production has been an increase of between $18/ha and $32/ha (Figure 32). However, with the positive yield impact, the average net impact on farm profitability has been between +$37/ha and $119/ha (average $103.75/ha). In 2020, the national farm income benefit derived from using the technology was $73.7 million and cumulative farm income gain since 2003 has been $851 million.

Figure 32: Farm level income impact of using GM IR maize in Philippines 2003-2020 ($/ha)



3.2.1.8 Colombia

GM IR maize was first grown commercially in 2006, initially on a restricted basis and post 2007, on an unrestricted basis. In 2020, GM maize was planted on 96,250 ha, of which 92.5% contained both IR and HT traits. Based on analysis summarised in Brookes (2020), which draws on research by Mendez et al (2011) and Celeres (2017 and 2019), the average yield gain from improved pest control has been +17.1%, with average savings on pest control costs of $44.6/ha. The net impact on costs of production has been marginally negatives, due to the average cost of the technology of $47.7/ha. When the yield gain is taken into consideration, significant average farm income gains have occurred, equal to $263/ha (2006-2020). At the national level, these farm income gains were $17.6 million in 2020 and cumulatively since 2006 have been $214.8 million.

3.2.1.9 Vietnam

GM stacked maize (HT and IR traits) was first planted commercially in 2015, and in 2020 was planted on 92,000 ha (9.7% of the total crop). Based analysis by Brookes (2017) and Brookes and Dinh (2021), the yield gain attributable to the IR trait was estimated to be about +7% in the first two years and +10.2% in the period 2019-2021 (average all years +9%). Coupled with an average cost of technology of $29.08/ha (IR trait only), the average farm income gain over the six years of adoption has been $119.82/ha (inclusive of average insecticide cost savings of $49.52/ha). At the national level, this equates to an aggregate net farm income gain of $12 million in 2020 and $37.9 million 2015-2020.

3.2.1.10 Other countries

Uruguay. GM IR maize has been grown in Uruguay since 2004, and in 2020, 82% (117,690 ha) of the crop used seed containing this technology. Using Argentine data as the basis for assessing impact, the average farm income gain over the 2004-2020 period has been +$33.35/ha. In 2020, the aggregate income gain was $4.2 million and cumulatively the farm income gain has been $46.8 million.

Honduras. Here farm level 'trials' have been permitted since 2003, and in 2020, 38,000 ha used GM IR traits (12% of the crop). 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. No seed premium 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 2020 was $5.8 million and cumulatively since 2003 the income gain has been $32.4 million.

Paraguay. The first commercial crop of maize using this technology was grown in 2013-14. In 2020, 72% 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 has been +$21.9/ha ($24.8/ha in 2020). At the national level, this is equivalent to a total farm income gain of $12.8 million in 2020 and over the eight years, the total farm income benefit has been $71 million.

3.2.1.11 Summary of economic impact

In global terms, the farm level impact of using GM IR maize was $2.79 billion in 2020. Cumulatively since 1996, the benefit has been (in nominal terms) $49.7 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 2020, the additional farm income generated by the technology is equal to a value-added equivalent of 6.1%. Relative to the value of global maize production in 2018, the farm income benefit added the equivalent of 2.8%.

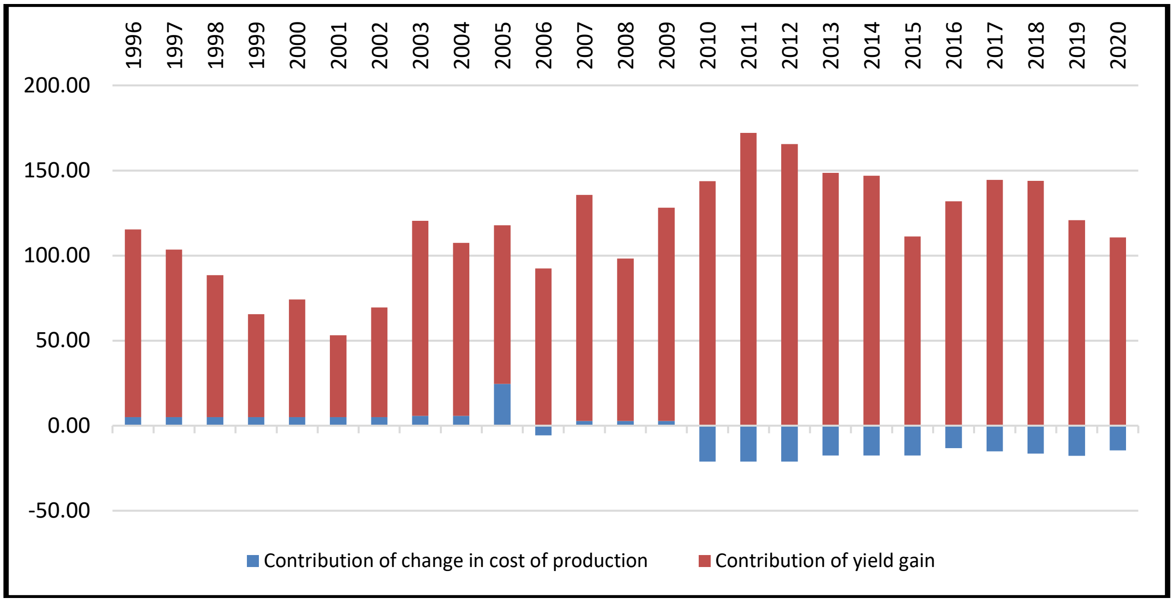
3.2.2 Insect resistant (Bt) cotton (GM IR)

3.2.2.1 The US

GM IR cotton has been grown commercially in the US since 1996, and in 2020 was used on 88% (3.03 million ha) of total cotton plantings. The farm income impact of using GM IR cotton is summarised in Figure 33. 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) in the first twelve years of adoption. With the move to the increasing adoption of the second generation of the technology since then, the average cost of the technology has been greater than the average saving in pest control costs, with all of the income gains arising from yield gains (Figure 33).

Overall, average profitability levels increased by between $53/ha-$115/ha with the first generation of IR cotton (with a single Bt gene) and by between $87/ha and $151/ha in 2003-2020 with the second generation of IR cotton (containing two Bt genes and offering a broader spectrum of control). Overall, the average farm income gain (1996-2020) has been $110.83/ha. The net aggregated farm income gain in 2020 of $291.3 million. Cumulatively, since 1996 the farm income benefit has been $7.07 billion.

Figure 33: Farm level income impact of using GM IR cotton in the US 1996-2020 ($/ha)



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. Average cost of technology: 1996-2020 $49.03/ha
4. Average insecticide cost savings 1996-2020: $41.77/ha

3.2.2.2 China

China first planted GM IR cotton in 1997, since when the area planted to GM IR varieties has increased to 95% of the total 3.09 million ha crop in 2020.

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 2020, the average increase in profitability was +$511.67/ha and for the period 1996-2020 has been $376.6/ha. At the aggregate level, the net national gain was $1.58 billion and cumulatively since 1997 the farm income benefit has been $26.27 billion (Table 14).

Table 14: Farm level income impact of using GM IR cotton in China 1997-2020

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	347	1,401.2
2015	28.3	338	1,223.9
2016	26.07	476	1,445.9
2017	26.59	470	1,425.5
2018	26.19	469	1,493.4
2019	25.07	448	1,468.1
2020	25.11	512	1,579.8

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 saving 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. Average cost of technology 1996-2020 $53.08/ha
6. 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

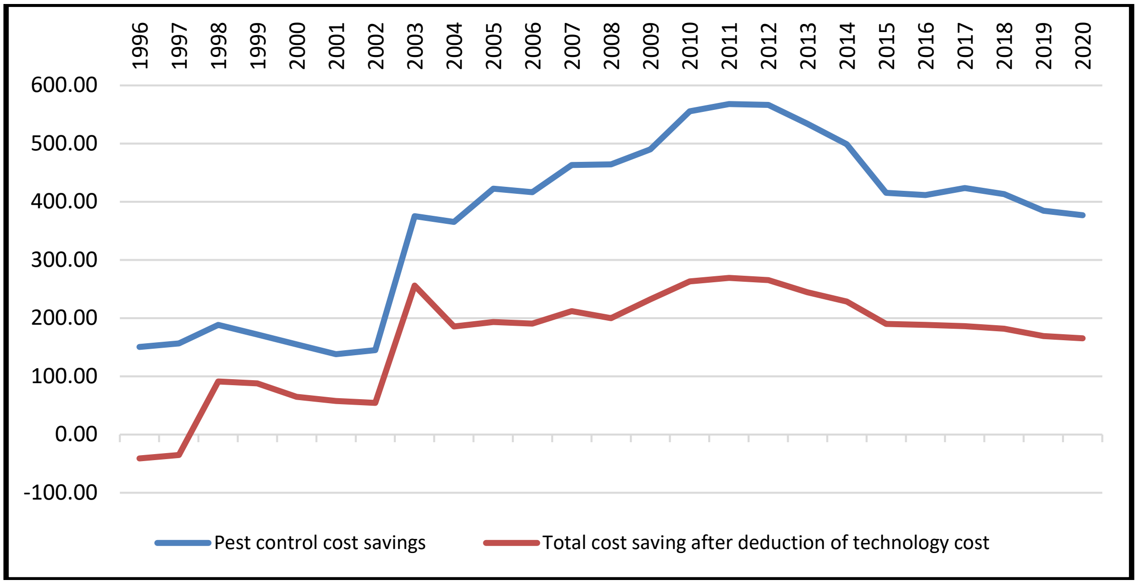
3.2.2.3 Australia

Australia planted 95% of its 2020 cotton crop (total crop of 280,000 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 seed technology); with the primary farm income benefit being derived from lower costs of production (Figure 34). 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;
- From the mid-2000s, 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 between $186/ha to $270/ha. The average increase in farm income over the period 1996-2020 has been $204.91/ha;
- At the national level in 2020, the net farm income gain was $44.3 million and cumulatively since 1996 the gains have been $1.136 billion.

Figure 34: Farm level income impact of using GM IR cotton in Australia 1996-2020 ($/ha)



Sources and notes:

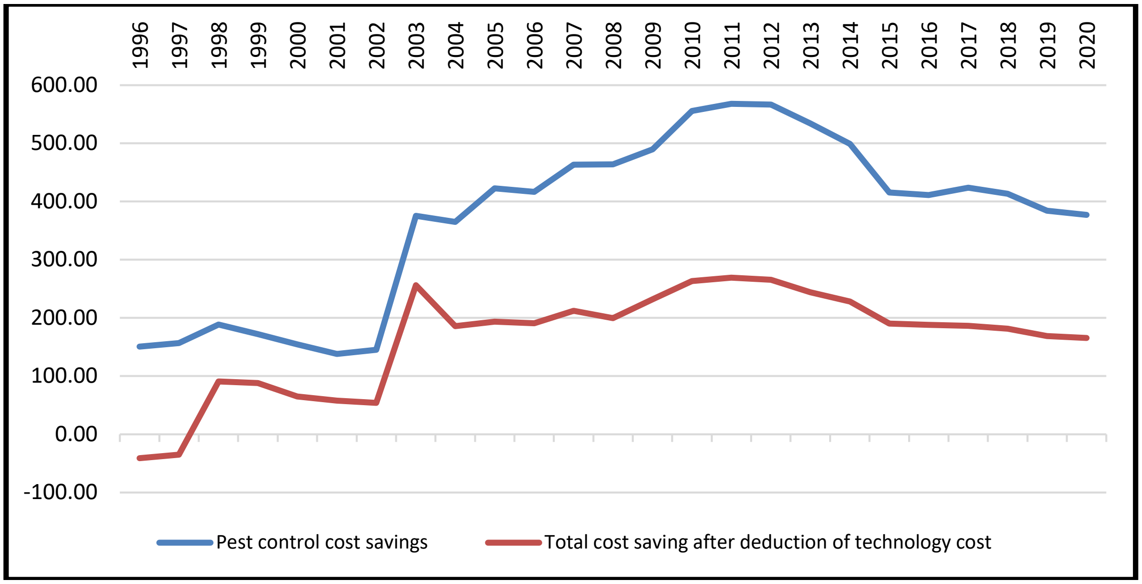
1. Impact data based on Fitt (2001) and CSIRO for Bollgard II since 2004
2. Average cost of technology 1996-2020: $233.94/ha
3. All values for prices and costs denominated in Australian dollars have been converted to US dollars at the annual average exchange rate in each year

3.2.2.4 Argentina

GM IR cotton has been planted in Argentina since 1998. In 2020, it accounted for 98% (441,000 ha) 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 technology[45]. In terms of gross margin, cotton farmers have gained between $25/ha and $317/ha annually during the period 1998-2018[46]. The average increase in farm income over the period 1998-2020 has been $234.1/ha. At the national level, the farm income gain was $90.9 million in 2020 (Figure 35). Cumulatively since 1998, the farm income gain from use of the technology has been $1.24 billion.

Figure 35: National farm income impact: GM IR cotton in Argentina 1998-2020 (million $)



Sources and notes:

1. Impact data (source: Qaim & De Janvry (2002) and for 2005 and 2006 Monsanto LAP, although the cost of technology in 2005 from Monsanto Argentina). Area data : source ArgenBio
2. Yield impact +30%, average cost of technology 1998-2018 $50.37/ha, cost savings (reduced insecticide use) in the last seven years $54/ha-$69/ha (average 1999-2020 $53.61/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

3.2.2.5 Mexico

GM IR cotton has been planted commercially in Mexico since 1996. In 2020, GM IR cotton was planted on 103,305 ha (69% 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 twelve years (average gain of 11.5% 1996-2020). In addition, there have

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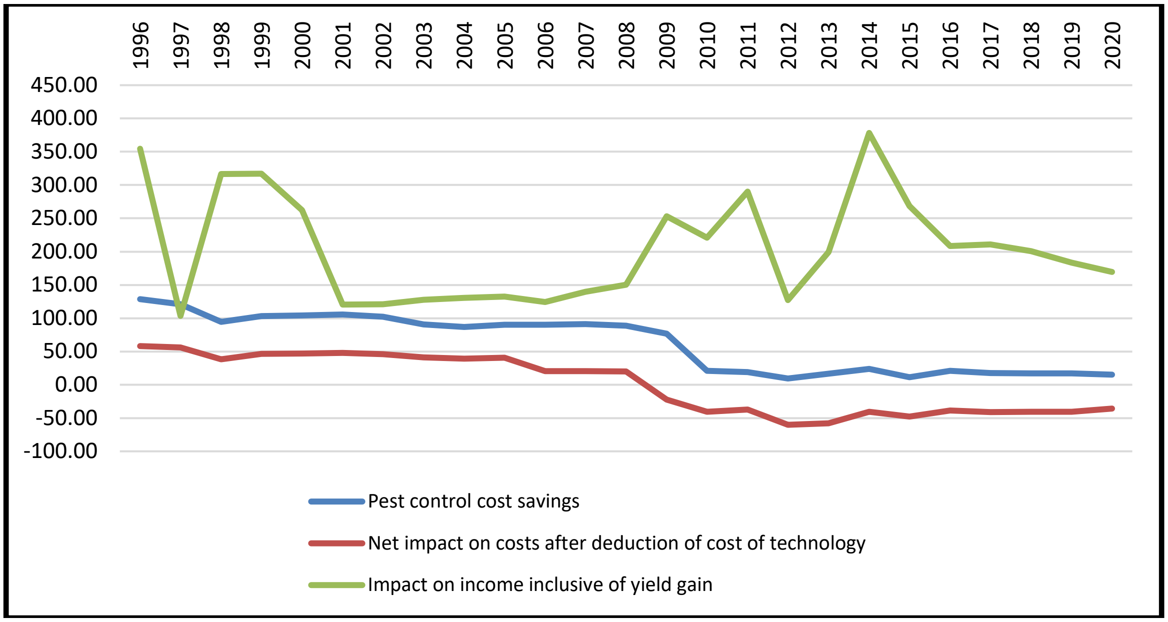
[45] The cost of the technology used in the years up to 2004 was $86/ha (source: Qaim & DeJanvry). From 2005, the technology cost assumption has been 116 pesos/ha ($20/ha- $40/ha: source: Monsanto Argentina). The average technology cost 1999-2018 was $28.17/ha

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

been important savings in the cost of production (lower insecticide costs). The 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, with an average value over the 1996-2020 period of $61/ha. The 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 data (Figure 36). Overall, the annual net increase in farm profitability has been within the range of $104/ha and $378/ha. At the national level, the farm income benefit in 2020 was $17.5 million (average of $169.6/ha) and cumulatively since 1996, the farm income benefit has been $407.4 million (average of $207.9/ha).

Figure 36: Farm level income impact of using GM IR cotton in Mexico 1996-2020



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: average 1996-2018 +11% (annual range +6% to +37%)
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

3.2.2.6 South Africa

In 2020, GM IR cotton[47] was planted on 95% (15,370 ha) of the 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 (Figure 37).

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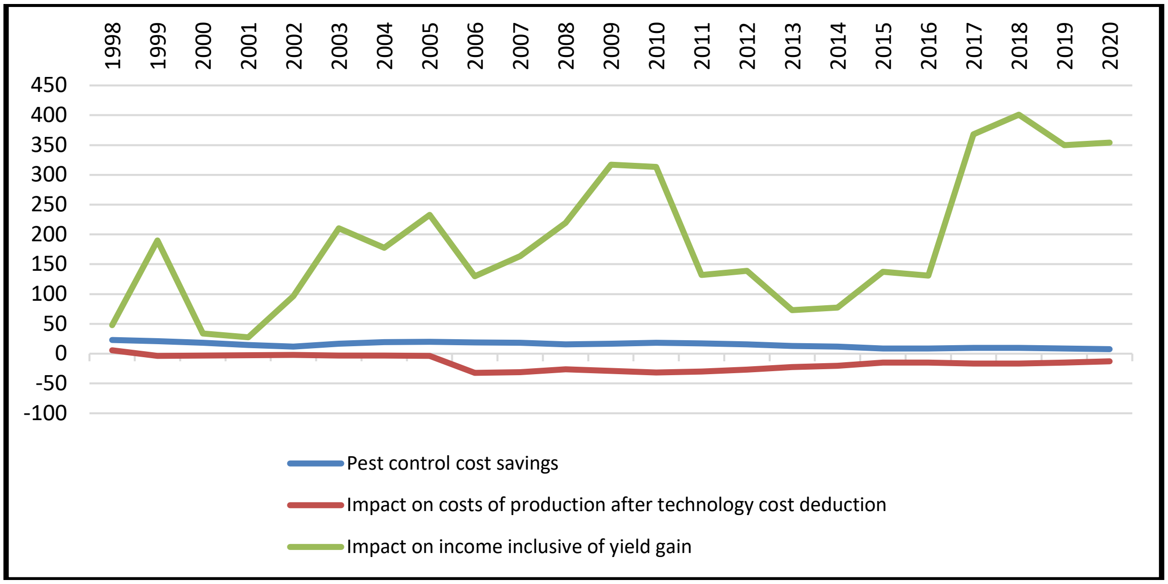
[47] First planted commercially in 1998

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 $400/ha (average gain of $224.5/ha 1998-2020).

At the national level, the aggregated farm income benefits have varied, largely in line with the changes in area planted to cotton (which has varied between 7,000 ha and 150,000 ha per year). Cumulatively since 1998, the farm income benefit has been $74.9 million.

Figure 37: Farm income impact: GM IR cotton in South Africa 1998-2020 ($/ha)



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) $8/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)

3.2.2.7 India

GM IR cotton has been planted commercially in India since 2002. In 2020, 12.22 million ha were planted to GM IR cotton which is equal to 94% of total plantings.

The main impact of using GM IR cotton has been major increases in yield[48]. With respect to cost of production, the average cost of the technology (seed premium: $49/ha to $54/ha) up to 2006

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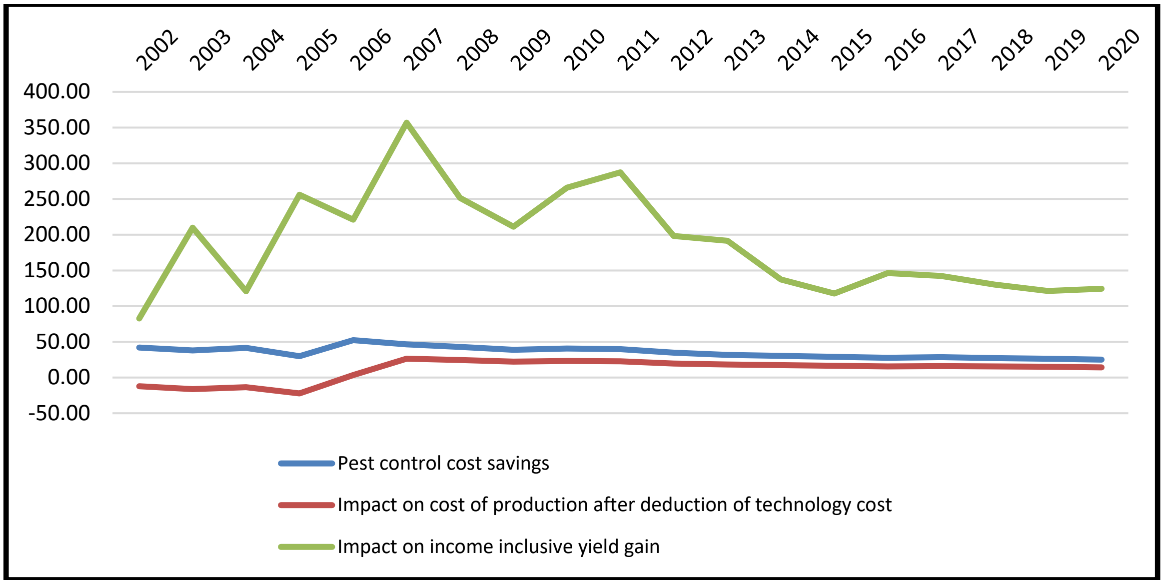
[48] Bennett et al (2004) found average yield increases of 45% in 2002 and 63% in 2003 (average over the two years of 54%) relative to conventionally produced cotton. Survey data from Monsanto (2005) confirmed this high yield impact (+58% reported in 2004) and from IMRB (2006) which found an average 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%

was greater than the average insecticide cost savings of $31/ha-$58/ha resulting in a net increase in costs of production (Figure 38). Following the reduction in the seed premium in 2006 to between $12/ha-$20/ha, farmers have made a net cost saving of $16/ha-$25/ha. The average seed premium for the period 2002-2020 has been equal to $15.4/ha. Coupled with the yield gains, important net gains to levels of profitability have been achieved of between $82/ha and $356/ha (the average increase in farm income 2002-2020 has been $181.8/ha). At the national level, the aggregate farm income gain in 2020 was $1.52 billion and cumulatively since 2002 the farm income gains have been $27.4 billion.

Figure 38: Farm level income impact of using GM IR cotton in India 2002-2020 ($/ha)



Sources and notes:

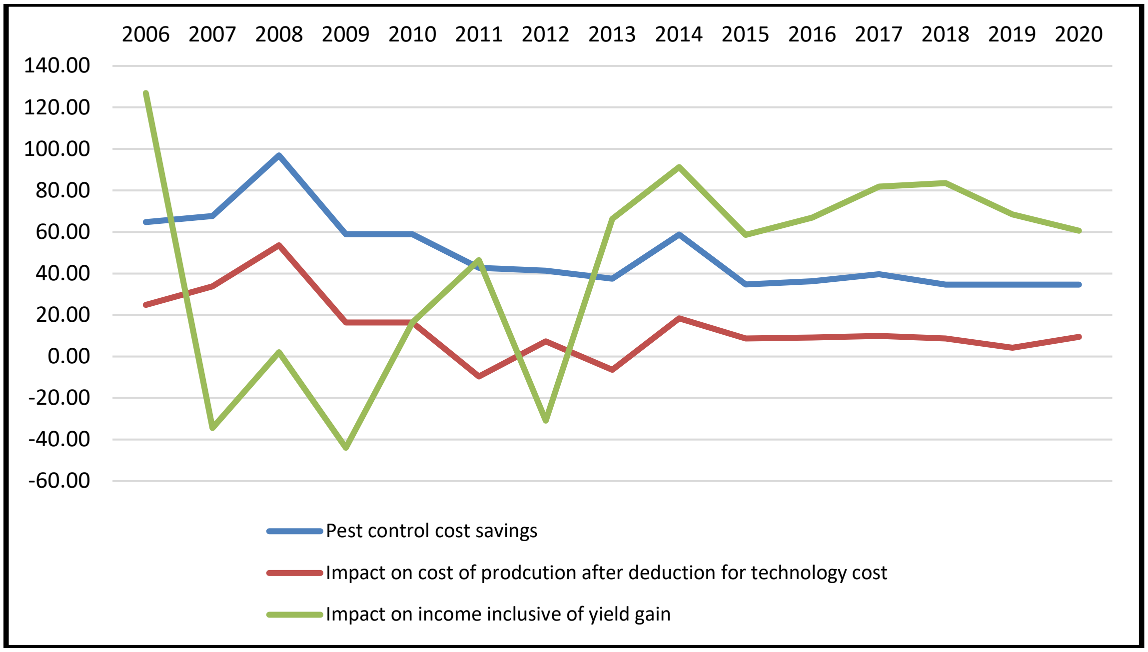
1. Impact data based on Bennett et al (2004), IMRB (2005 & 2007), Gruere (2008), Qaim (2009), Herring and Rao (2012)
2. All values for prices and costs denominated in Indian Rupees have been converted to US dollars at the annual average exchange rate in each year

3.2.2.8 Brazil

GM IR cotton was planted commercially in Brazil for the first time in 2006, and in 2020 was planted on 1.17 million ha (77% of the total crop). The area planted to GM IR cotton in the early years of availability 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. In subsequent years, however, improved conventional varieties in which the GM IR trait was not present 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 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: Figure 39). 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 in a range of -1.8% to +3% relative to the best performing conventional varieties.

Based on these yield findings, an average seed premium of $47.54/ha and average insecticide costs savings of $61.95/ha, the average net farm gain derived from using this technology over the period 2006-2020 has been $86.26/ha. At the national level this equates to an aggregate net income gain of $70.8 million in 2020 and cumulatively, since 2006, of $435.1 million.

Figure 39: Farm level income impact of using GM IR cotton in Brazil 2006-2020 ($/ha)



3.2.2.9 Colombia

GM IR cotton has been grown commercially in Colombia since 2000, with this technology used in about 54% of the, 8,617 ha total crop (in stacked seed offering herbicide tolerance and insect resistance).

Based on analysis summarised in Brookes (2020), which draws on research by Zambrano et al (2009), Fonseca and Zambrano (2010) and Celeres (2017 and 2019), the main impact has been a significant improvement in yield[49]. Studies have identified a wide range of yield benefits by region (eg, a range of +9% to +75%, with an average yield gain of +35%: Zambrano et al, 2009) from improved pest control, coupled with savings on pest control costs (of between $41/ha and £63/ha: average of $55/ha). The net impact on costs of production has been negative, due to the average cost of the technology of $97/ha relative to the average pest control cost saving of $55/ha. However, when the yield gain is taken into consideration, significant average farm income gains have occurred, equal to $292/ha (2006-2020). At the national level, these farm income gains were £1 million in 2020 and cumulatively since 2003 have been $100 million.

3.2.2.10 Other countries

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. Since 2016, no GM IR cotton has been grown because of a temporary ban imposed by the government. This was due to difficulties in selling the cotton from the varieties containing the trait because the fibres are shorter than most markets want (note this is not related to any impact of the GM IR technology but relates to the varieties containing the technology).

Pakistan: After widespread ‘illegal’ planting of GM IR cotton in Pakistan for several years, it was officially permitted in 2009 and in 2020, 95% of the crop (2.09 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 to 2015. 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. Since 2016, the average yield gain assumption has been reduced (to 10% by 2020) in line with declining levels of control of the pink bollworm pest by the technology. For 2020, the estimated average farm income benefit was $63.9/ha. At the national level this is equal to a net farm income gain of $133.7 million. Cumulatively since 2009, the farm income benefit of using this technology is $5.53 billion.

Myanmar: GM IR cotton has been grown in Myanmar since 2007 and in 2020, 213,600 ha (89% 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

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[49] Although it should be noted that the early years of adoption of the stacked traited seed, yield performance was poor relative to conventional varieties because the technology was not available in some of the leading varieties and/or in varieties suited to growing in some regions – see Brookes, 2020 for additional discussion

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 2020 was $224.8/ha, which at the national level amounts to a gain of $48 million. Cumulatively the average farm income gain since 2007 has been £178/ha, with a national level gain of $552.7 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.

3.2.2.11 Summary of global impact

In global terms, the farm level impact of using GM IR cotton was $3.8 billion in 2020. Cumulatively since 1996, the farm income benefit has been $70.6 billion. Within this, 84% of the farm income gain has derived from yield gains (less pest damage) and the balance (16%) 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 2020, the additional farm income generated by the technology is equal to a value-added equivalent of 11.8%. Relative to the value of global cotton production in 2020, the farm income benefit added the equivalent of 11.6%.

3.3 Other GM crops

3.3.1 Maize/corn rootworm resistance

GM IR (resistant to corn rootworm (CRW)) maize has been planted commercially in the US since 2003. In 2020, there were 11.2 million ha of maize planted containing GM IR traits for the control of CRW (34% of the total US crop).

The main farm income impact[50] has been higher yields of about 5% relative to conventional maize. In addition, there has been an average insecticide cost saving of $24.9/ha (average across all of the area planted to CRW resistant maize: range of $23/ha-$39/ha[51]). The average cost of the technology over the period 2003-2020 has been $25.19/ha, illustrating that there has been a marginal overall increase in the cost of production. However, after taking into consideration the positive yield impact of the technology, the net impact on farm profitability has been between an

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

[51] 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. Thus, the average insecticide cost saving across the area traditionally using insecticides for the control of CRW in 2020 was $40.9/ha, which divided across the total area of maize using GM IR CRW control seed was $26.3/ha

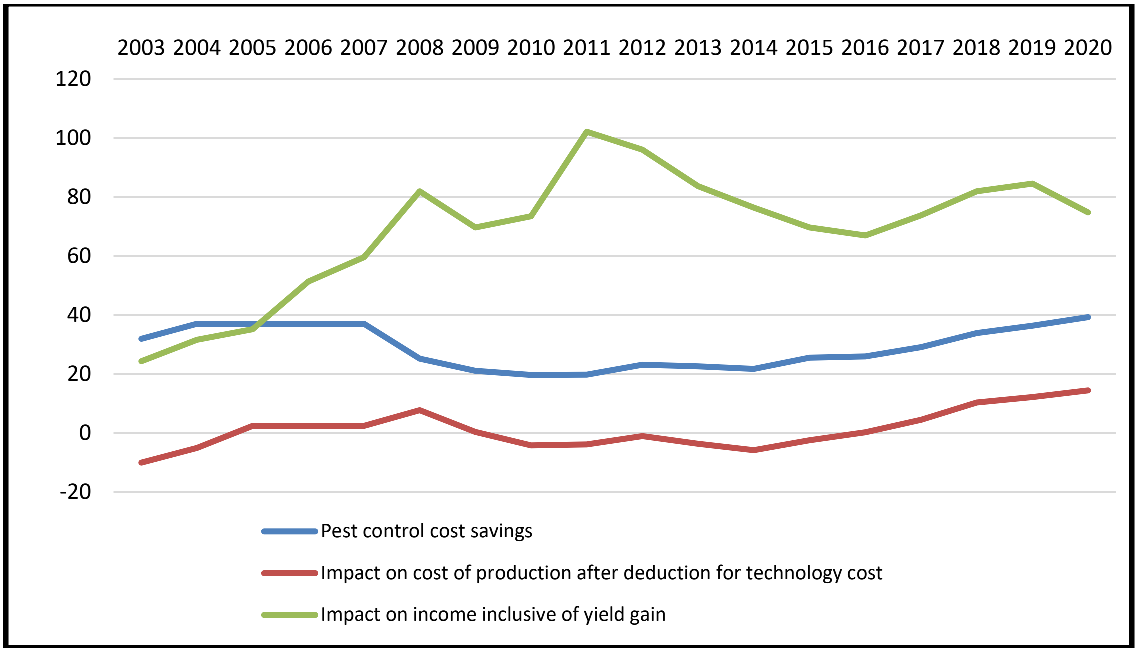
average increase in income over the 2003-2020 period of $77.5/ha (annual range of +$24/ha to +$102/ha: Figure 40).

At the national level, aggregate farm income increased by $840 million in 2020. Cumulatively since 2003, the total farm income gain from the use of GM IR CRW technology in the US maize crop has been +$17.42 billion.

GM IR CRW traited-seed was also planted commercially for the first time in 2004 in Canada. In 2020, the area planted to CRW resistant varieties was 0.73 million ha (52% of the crop). Based on US costs, insecticide cost savings and yield impacts, this has resulted in additional income at the national level of $58.3 million in 2020 (cumulative total since 2004 of $652.9 million).

At the global level, the extra farm income derived from GM IR CRW maize use has been $18.07 billion.

Figure 40: Farm level income impact of using GM IR CRW control maize in the US 2003-2020 ($/ha)



Sources and notes:

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

3.3.2 Virus resistant papaya

Ringspot resistant papaya has been commercially grown in the US (State of Hawaii) since 1999, and in 2020, 77% of the state's papaya crop was GM virus resistant (187 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 yield increase of biotech papaya relative to conventional crops has been within a range of +15% to +77% (17% in 2020).

In terms of profitability[52], the net annual impact has been an improvement of between $2,400/ha and $11,400/ha, and in 2020, this amounted to a net farm income gain of $1,515/ha and an aggregate benefit across the state of $0.28 million. Cumulatively, the farm income benefit since 1999 has been $36.4 million.

Virus resistant papaya are also reported to have been grown in China, (9,500 ha in 2020). No impact data on this technology has been identified.

3.3.3 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 2020[53] (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 2020, added a net gain to users of $10.5 million. Cumulatively, the farm income benefit since 2004 has been $329.6 million.

3.3.4 Drought tolerant maize

Drought tolerant maize has been grown in parts of the US since 2014, and in 2020 was planted on 1.42 million hectares. Drawing on yield comparison data with other (non- GM) drought tolerant maize and field trials data (source: Monsanto US Field Trials Network in the Western Great Plains), this suggests that the technology is providing users with a net yield gain of 2.3% to 2.6% and a small cost saving in irrigation costs[54]. After taking into consideration, the additional cost of the seed compared to non-GM drought tolerant maize, the average gross farm income gain over the seven-year period of use has been $16.7/ha. In 2020, this resulted to an aggregate farm income gain of about $35.3 million and over the period 2014-2020, a total gain of $131.8 million.

3.3.5 Insect resistant brinjal

Insect resistant brinjal (resistant to the brinjal fruit and shoot borer), has been grown in Bangladesh since 2014, and in 2020, it was grown on 13% (6,310 ha) of the country’s crop.

Drawing on analysis by Mondal and Akter, (2018), Prodhan et al, (2018), Ahmed et al, (2019) and Shelton, (2020), the main impacts of the technology have been higher yields (+15% to +20%), better quality produce (equivalent to a 10% higher price paid for fruit) and lower costs of pest control equal to about $88/ha. The cost of the technology has to date been zero with the

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

[53] Mostly found in Georgia and Florida

[54] A 7% water saving applied to a baseline cost from the USDA ERS Prairie Gateway region which is where most DG maize is grown

technology being made available freely by the extension service. As a result, the net impact on farm income has been positive, with an average increase in farm income over the period 2014-2020 of +679/ha (annual range of between +$616/ha and +$704/ha). At the national level, the cumulative fam income benefit from using this technology since its first introduction in 2014 has been $9.75 million.

3.3.6 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.

Lastly, GM potatoes that convey resistance to late fungal blight in potatoes and offer traits that improve potato quality in terms of reduced bruising and browning, lower acrylamide levels and lower levels of reducing sugars have also been grown commercially on a small-scale, in the US since 2014 (1,780 ha in 2020), and in Canada since 2017 (40 ha in 2020). No impact analysis is presented here due to the lack of published studies on the subject.

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 1.28 million ha of GM alfalfa were being cropped in 2020. The technology is reported to offer improved weed control, better yields and higher quality forage. No impact analysis is presented here due to the lack of published studies on the impact.

In addition, GM low lignin alfalfa has been available since 2016 and in 2020 was planted on about 120,000 ha. No impact analysis is presented here due to the lack of published studies on the impact.

3.4 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.

Many of the impact studies[55] 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;

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[55] 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)

- 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 maize relative to conventional and organic maize 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 season[56]. Also some Indian cotton growers 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 techniques[57] to obtain farmers' valuations of non-pecuniary benefits. A summary of these findings is shown in Table 15.

Table 15: 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 1996-2020

The approach used to estimate the non-pecuniary benefits derived by US farmers from biotech crops over the period 1996-2020 has been to draw on the values identified by Marra and Piggot (2006 & 2007) and to apply these to the GM crop planted areas in this period.

Figure 41 summarises the values for non-pecuniary benefits derived from GM crops in the US and shows an estimated (nominal value) benefit of $1.1 billion in 2020 and a cumulative total benefit (1996-2020) of $19.2 billion. Relative to the value of direct farm income benefits presented above, the non-pecuniary benefits were equal to 15% of the total direct income benefits in 2020 and 17.3% of the total cumulative (1996-2020) 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

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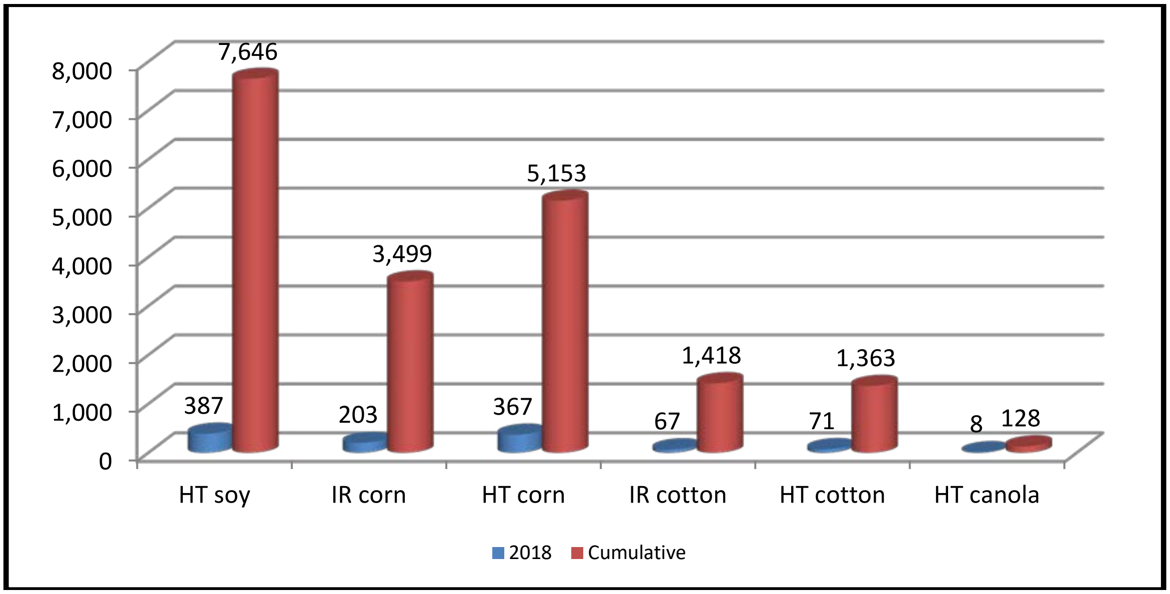
[56] Notably maize in India

[57] 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

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.

Figure 41: Non-pecuniary benefits derived by US farmers 1996-2020 by trait ($ million)



3.5 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 16).

Table 16: Additional crop production arising from positive yield effects of GM crops (million tonnes)

	1996-2020	2020
Soybeans	330.35	33.48
Maize	594.58	47.9
Cotton	37.01	2.26
Canola	15.77	1.00
Sugar beet	1.87	0.15

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

The GM IR traits, used in maize and cotton, have accounted for 91.1% of the additional maize production and 98.2% 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[58]) when

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[58] 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

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 25 years since 1996 has been +17.7% for maize and +14.5% for cotton (Table 17).

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 222.7 million tonnes to soybean production in Argentina and Paraguay between 1996 and 2020. The remaining additional GM-related soybean production has come from the second generation of GM HT soybeans grown in North American countries since 2008 and where the GM HT technology has enabled farmers to obtain higher yield via improved levels of weed control, with Intacta soybeans having added a further 44.4 million tonnes since 2013.

Table 17: Average (%) yield gains GM IR cotton and maize 1996-2020

	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	11.6	N/a	24.0
Honduras	23.9	N/a	N/a
Mexico	N/a	N/a	11.0
Argentina	5.8	N/a	30.0
Philippines	18.1	N/a	N/a
Spain	11.6	N/a	N/a
Uruguay	5.5	N/a	N/a
India	N/a	N/a	29.0
Colombia	17.1	N/a	25.0
Canada	7.0	5.0	N/a
Brazil	11.5	N/a	1.8
Pakistan	N/a	N/a	18.0
Myanmar	N/a	N/a	30.5
Australia	N/a	N/a	Nil
Paraguay	5.5	N/a	Not available
Vietnam	9.0	N/a	N/a

Notes: N/a = not applicable

4 The environmental impact of GM crops

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

a. Impact associated with insecticide and herbicide use.
b. Impact on carbon emissions.

These are presented in the sub-sections below.

4.1 Impact associated with insecticide and herbicide use

The control of pests and reduction of weed competition in agricultural production systems is vital if adequate quantities of good quality food are to be consistently made available to feed the (growing) world's population. The primary way in which this has been delivered in global agriculture has been through the use of pesticides which have therefore made important contributions to improving crop yields, the quality of produce and in turn, improved global food security (Cooper and Dobson, 2007, Aktar, Sengupta and Chowdhury, 2009). However, despite these benefits, pesticides can be hazardous to humans and the environment, having the potential to disperse into the environment and contaminate/poison non-target species. The consequences of pesticide use have been documented and discussed by many (eg, Bourget and Guillemaud, 2016, Sud, 2020), with pesticide regulatory systems in place '*to balance the societal and economic benefits with the unintentional and undesirable environmental and health impacts'* (Lewis et al, 2021).

Against this background, the regulatory approval and subsequent widespread commercial availability of GM crops in the mid-1990s ushered in a major change to how some pests and weeds were controlled in the crops where the seed technology has become widely used (canola, cotton, maize and soybeans).

An important component of any assessment of the environmental impact of widespread GM crop cultivation is therefore identifying how their use has impacted on pest and weed control practices and, in particular on how insecticide and herbicide use has altered. In turn, this requires comparisons of the respective weed and pest control measures used on GM versus the 'conventional alternative' form of production and how these may disperse into the environment and have negative consequences for non-target species. This presents a number of challenges.

How to measure environmental and human health impacts: an appropriate indicator
The challenge to developing an appropriate indicator for evaluating potential non-target effects of pesticide use requires taking account of differences in terms of environmental and human health impacts of the numerous pesticide active ingredients used and be sensitive enough to take account of differences to the amount (of each) applied to crops. An indicator also needs to adaptable enough to take account of changes in the availability of pesticides via the withdrawal of some from use and the introduction of new chemistry to the marketplace.

To assess the risks and impact of pesticide use in a consistent but simplified manner a number of indicators have been developed. Some of these are hazard-based, whilst others try to consider risk.

The most common (and crudest) form of indicator used (and which has been most commonly been presented in the literature relating to the impact associated with GM crop use) has been simply to examine impact in terms of the volume (quantity) of pesticide active ingredient applied under the principle that 'more is bad for the environment and less is better for the environment'. Whilst this approach is sensitive enough to take account of changes in the amount applied and can accommodate the changing availability of different active ingredients, it is not a good measure of environmental impact because the toxicity of each pesticide is not directly related to the amount (weight) applied and there is consideration of how the active ingredients disperse into the environmental or may affect non target species.

There exist alternative measures that could be used. These include:

- The Environmental Impact Quotient (EIQ) developed at Cornell University by Kovach et al (1992) and updated annually. This hazard-based indicator is one of the earliest indicators developed and uses a scoring system approach to determine the impact of a pesticide on humans, groundwater and bio-diversity. Rating values are given for effects on farm workers, consumers, toxicity to beneficial insects, toxicity to bees, fish and birds, plant surface half-life, chronic health effects, run off and leaching potential, soil residue half-life and mode of action. These are added to produce a single EIQ rating per active ingredient, with the EIQ indicator value for each active ingredient determined by the amount applied;
- The Environmental Yardstick for Pesticides developed in the Netherlands, which quantifies risk of pesticide use at the field, regional and national level by allocating environmental impact points for risks to groundwater, aquatic species and soil organisms (Reus and Leenderste, 2000);
- SYNOPS indicator, developed to support the German National Action Plan on the Sustainable Use of Plant Protection Products (Strassemeyer and Gutsche, 2010) which assess the acute and chronic pesticide risks to soil and surface water and non-target pollinator species through the calculation of Predicted Environmental Concentrations (PECs);
- The Norwegian pesticide risk indicator (NERI) was developed both as a tool to assess pesticide use risk and as a method for taxation of pesticides (Stenrød et al, 2008). It uses a rating system for human health impacts (4 risk classes according to the risk phrases on product labels) and environmental risk by adding up rating scores for effects on earthworms, bees, birds, aquatic organisms, mobility and leaching potential, persistence, bioaccumulation and formulation type. The accumulated rating scores are then used to classify pesticides into three environmental risk classes and grouped into several classes subject to different tax levels;
- Like NERI, the Pesticide Load (PL) risk indicator developed in Denmark was primarily developed to form the basis for a national pesticide tax system (Kudsk et al, 2018). The indicator is made up of three categories of indicator that aim to measure the potential pressure on human health, environmental fate and ecotoxicity. This does not measure actual impact but aims to reflect the relative environmental pressures from the differing hazards of each pesticide and the amount of each applied. In relation to the environmental fate ecotoxicity indicators, pesticide loading points for each pesticide is measured against a benchmark reference substance that is classified as the most harmful active ingredient for each parameter (eg, longest soil half-life) and all other substances are expressed relative to this reference active ingredient;

- Total Applied Toxicity (TAT). This indicator uses regulatory threshold levels for impacts of pesticide active ingredients on eight different groups of non-target species as indicators of potential impact on bio-diversity (Schulz et al, 2021). The authors applied this approach to assess environmental impacts associated with insecticide and herbicide use in maize and soybeans in the US;
- The Ecological Relative Risk (EcoRR) indicator (Sanchez-Bayo et al, 2002). This is a site-specific indicator that assesses and compares the ecotoxicological risk of pesticides on ecosystems. It compares relative risks between different pesticides and assesses the potential ecological impact of their residues. The EcoRR approach is based on standard frameworks for risk assessment (eg, Predicted Environmental Concentration (PEC) or toxicity) but takes account of factors such as persistence of residues and biodiversity of ecosystems;
- The European Union's Harmonised Environmental Indicators for Pesticide Risk (HAIR) is a set of indicators developed for calculating trends in aggregated risks associated with the agricultural use of pesticides. This is a series of models for the evaluation of the environmental fate of pesticides (eg, PEARL - Pesticide Emission Assessment at Regional and Local scales that model's pesticide behaviour in the soil-plant system). It has been used to classify pesticides used in European agriculture into different risk categories so as to set a baseline for the reduction in the aggregate level of risks associated with pesticide use. Success (or failure) in this goal is largely determined via monitoring and collecting data on the sales of products in each pesticide risk category, with sales figures used as a proxy for use (and ultimate impact).

Whilst the list of indicators above represent some, not a full list of those available, it highlights the range of indicators, each of which was originally developed with a specific purpose in mind (eg, as a vehicle for establishing a pesticide tax) and/or targeting specific local, regional or national impact assessment. Hazard based indicators do not assess risk or probability of exposure to pesticides typically rely to some extent on qualitative assumptions and ratings drawn from product label and regulatory threshold information for the scaling and weighting of (quantitative) risk information. This can result, for example in the case of the EIQ indicator, in a low risk rating for one factor (eg, impact on farm workers) possibly cancelling out a high-risk rating factor for another factor (eg, impact on ecology). Other models or indicators that attempt to include risk of exposure into the assessments typically require site-specific or local/regional level data on issues such ground water levels or soil structure or at least the application of standard scenario models for exposure at a number of locations. This is why indicator/models such as SYNOPS was developed for specific applicability to Germany are country-specific in their application and replication/adaption of such models to other countries (as is the case in respect of Norway and Switzerland) is difficult, time consuming and requires adaption to reflect differing levels of information.

For the purposes of our analysis, an indicator is required that is readily available and applicable across a range of crops (notably the four main crops where GM crop technology is widely used), grown in more than 20 countries on an area of approximately 186 million hectares (2020). This encompasses a wide range of climates, soil types, weather, agricultural production systems, eco-systems, non-target species and pest and weed control practices. Whilst a risk rating type model such as SYNOPS might represent an ideal to utilise, the transferability/applicability of such an exercise to this context is undeliverable.

The indicator that has been used most by various analysts to assess the environmental impact associated with changes to pest and weed control practices with the growing of GM crops has been the EIQ. It was originally developed to allow for the comparison of the environmental impact of different crop protection systems used as more integrated forms of pest and weed control were introduced in the US, in the 1990s. Its early adaption and use in respect of the use of GM crop technology relative to conventional (non-GM) cropping was made by Brimner et al, 2004 and Kleiter, 2005, with this author also using it first in 2005. It has also subsequently been used by others (eg, Biden et al, 2018). As indicated above, the EIQ integrates the various rating values for effects on farm workers, consumers, toxicity to beneficial insects, toxicity to bees, fish and birds, plant surface half-life, chronic health effects, run off and leaching potential, soil residue half-life and mode of action to produce a single EIQ rating per active ingredient, with the EIQ indicator value (or field EIQ) for each active ingredient determined by the amount applied. 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 sum of the field EIQ/ha for each pesticide used for a conventional (non-GM) versus GM crop production system, 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 author of this analysis have 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) is transferable and relatively easy to use/apply across crops and production systems across the many diverse regions and countries where GM crops have been widely grown;
- 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.

Whilst utilising the EIQ indicator in this analysis, the author acknowledges that it is only a hazard indicator and, as indicated above, it has important weaknesses. These have been discussed by others such as Peterson R and Schleier J (2014) and Kniss A and Coburn C (2015). 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. It is hoped that in the near future indicators that better consider risks of pesticide exposure and the fate of pesticides in the environment but at the same time are transferable and reasonably easy to use and apply to a variety of different cropping systems around the world.

Despite the acknowledged weaknesses of the EIQ as an indicator of environmental impact associated with pesticide use, the author of this paper continues to use it because no other indicator currently offers the scope for relatively easy transferability and use across a wide range of crops, and countries. In this paper, the EIQ indicator is used in conjunction with examining changes in the amount of pesticide active ingredient applied to GM crops relative to conventional (non-GM) crops.

Availability and representativeness of data.
Assessing the environmental impact associated with crop protection and weed control practices used with GM crops relative to conventional alternatives, requires making comparisons of the methods used, most notably relating to the use of insecticides and herbicides. Such 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 fairly limited (eg, Qaim and Traxler, 2005, Pray C, 2002) with even fewer (eg, Brookes, 2005, Brookes, 2009) especially in terms of providing data to the individual active ingredient level. Secondly, national level pesticide usage survey data is also limited. There are no published, detailed, annual pesticide usage surveys conducted by national authorities in any of the countries currently growing GM crop traits. Of the GM crop growing countries, the US, through the US Department of Agriculture (USDA) is the only country that regularly publishes pesticide usage surveys on some of the crops in which GM technology is used. However, these are not conducted on an annual basis for each crop (eg, the last time maize was included was 2018 and previous to this, in 2016, 2014, 2010 and 2005, for soybeans the last time included was 2020 and before that 2018 and 2015) and do not disaggregate usage by production type (GM versus conventional).

The only sources of pesticide usage data on the crops in which GM technology has been used around the world derive from two main sources:

- Ad hoc/bespoke studies of the impact of using GM crop technology relative to conventional alternative crops. These are typically crop specific and limited both in terms of time periods covered (1-3 years) and may be local in nature rather than reasonably representative of a national perspective;
- Private market research companies that undertake farm level surveys of crop-specific pesticide use on a regular basis. These are primarily conducted to collect data (typically to the product and brand level) in order to service the market intelligence and information requirements of businesses that sell crop protection products and can be found in many countries. The most comprehensive datasets from these sources typically focus on usage in the larger agricultural producing countries such as the US, Canada, Brazil, Argentina, Paraguay, South Africa, the EU, Australia, China and India. Access to these datasets requires the payment of subscriptions to the suppliers and typically comes with restrictions on the publication of disaggregated levels of data (in particular to the brand and product level). With the exception of the data available relating to pesticide use on a limited range of crops in the USA, this source of data does not differentiate between use of active ingredients or products by production type (GM versus conventional).

In this analysis, the author draws on both categories of data. This includes reviewing literature on published GM crop impact studies both on peer reviewed and other literature. It draws on relevant publicly available pesticide usage survey data (primarily USDA) and has accessed private market research sources from the primary providers over the last 20 years, most notably Kynetec and Kleffmann, which have both collected pesticide usage data on many crops in a number of countries around the world. Access to these private sources of data has been facilitated by the primary sponsor of this study – Bayer Crop Science. Details of the sources used for analysis by crop and country are detailed in Appendix 2. This means that this analysis draws on the most comprehensive and detailed sources of pesticide usage available at a global level. It also means that the EIQ indicator calculations made in the course of the analysis takes into consideration all of the main pesticides used in the production of the crops where GM crop technology is used. For example, in the US, this relates to about 55, 50 and 40 herbicides respectively used in soybeans, maize and cotton crops, in Brazil, 40 and 30 herbicides respectively used on soybean and maize crops and in Argentina, about 60 and 20 herbicides used on soybeans and maize. Similarly EIQ values associated with the use of about 30 insecticides used in cotton grown in Australia and India, 45 in China and about 50 in the US.

Whilst the research has accessed and utilised these comprehensive sources of (pesticide use) data, it is important to recognise the limitations than come with this data for the purposes of the analysis. A primary objective of the research is to assess the environmental impact of crop protection practice differences between production systems that use GM crop technology and those that use conventional technology (based on the EIQ indicator). In order to do this herbicide and insecticide usage changes with GM crop technology adoption require identification in terms of not only what is currently used with GM crops, but also in the 'counterfactual situation', that is, 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 reverted to using non-GM production methods).

The most straightforward way of doing this is from observations and surveys of crop protection practices on farms using the different production systems. As such, this source of data from ad hoc/bespoke surveys of usage on farms using GM versus non GM technology has been utilised in this analysis, where available. This category of data does not cover every trait, crop, country or year and therefore alternative sources and assumptions are required.

As indicated above, an important source of data used is the regular farm level pesticide usage survey data collected by private market research companies and made available on subscription. For all countries studied, with the exception of the US, this data source does not disaggregate usage for each active ingredient to production type (GM versus non-GM) and therefore this source has been used in the following way:

- Where GM-herbicide traited crops account for all or almost all (90% plus) of production in a country (eg, soybeans in all of the South American countries), the herbicide (and/or insecticide) usage data is assumed to represent the GM HT and/or GM IR crop;
- For conventional crops and GM HT/IR crops where the less than 90% of the crop is GM HT/IR, estimates of herbicide use in overall weed/pest control systems are based on information drawn from extension and industry advisors in each country (some of this derives from literature such as weed control guides from extension services and some from direct contact with advisors in such services, academics and industry representatives). In all cases, the aim has been to identify the weed/pest control practices that farmers might reasonably be expected to use (including typical herbicide and insecticide application rates) in both GM HT/IR and conventional crops. In relation to GM IR versus conventional crop pest control practices the focus has been on products used to control only the pests that the GM IR technology targets control (typically lepidopteran pests (and rootworm in North America) and not products used to control other categories of pests (eg, sucking pests and (cotton) weevils). In addition, in the early years of adoption of GM traited crops, the usage assumed for conventional crops has been cross checked with recorded usage levels in the years immediately prior to the introduction of GM technology to ensure that

usage levels derived from the extension service approach did not over (or understate) likely usage levels.

In the case of the US, where pesticide usage data for the crops of cotton, maize and soybeans is available at a disaggregated level (GM versus conventional crop), the approach used reflects the relative balance of the total crop accounted for GM versus conventional as follows:

- Recorded herbicide and insecticide usage (to the active ingredient level) for GM traited crops has been used for all years;
- Recorded herbicide and insecticide usage (to the active ingredient level) for conventional crops has been used for all years until the conventional share of total production fell below 30% of the crop (2001 for cotton and soybeans and 2007 for maize);
- For conventional cotton and soybeans post 2001 and maize post 2012, estimates based on extension service type sources have been used (statistical source: USDA NASS 2022).

In the case of the US analysis, the reasons why herbicide/insecticide usage levels identified for the increasingly small conventional crop were not used and have been replaced by usage patterns identified from 'extension service' type sources reflects the author's assessment that these levels of usage are unrepresentative of what might reasonably be expected if all of the (majority) area using GM technology reverted to conventional (non-GM) production systems. More specifically:

- Although pest/weed damage and competition varies by year, region and within region, farmers' who consistently farm conventionally rather than using GM seed 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 these pest/weed problems. In addition, late or non-adopters of new technology in agriculture are typically those who generally make less use of newer technologies than earlier adopters. As a result, insecticide/herbicide usage levels on non-adopting (conventional) farms tend to be below the levels that would reasonably be expected on an average farm with more typical pest/weed problems and where farmers are more willing to adopt new technology;
- Some of the farms continuing to sow conventional seed, use extensive, low intensity production methods (including organic) which feature, limited (below average) use of herbicides/insecticides. If the pesticide usage patterns of this sub-set of growers are used as a proxy to represent usage patterns if all farmers returned to farming without GM technology, this is likely to understate pesticide usage for the majority of farmers. For example, prior to the adoption of GM HT cotton in the US in the mid-1990s, when all of the crop was conventional, about 90% of the crop was typically receiving some use of herbicides for weed control and the average amount of herbicide used (kg/ha) and average EIQ/ha value for herbicide use on this crop were respectively about 2.54 kg ai/ha with 54/ha. Within this cotton farmers in Texas, where many producers practice extensive production systems (little or no use of inputs like pesticides), the average amount of herbicide active ingredient used and average EIQ/ha were respectively about 1.54 kg/ha and an average EIQ/ha of 31.1 (Texas then accounted for just under 60% of the US cotton crop). In 2020, the conventional cotton crop accounted for about 4% of the total crop (about 138,000 ha), of which 84% of the crop received some form of herbicide use as part of weed control and 80% of the crop was located in Texas. Using the recorded average usage figures for herbicide use in Texas in 2020 (about 1 kg ai/ha and an EIQ/ha value of about 21/ha) as

a proxy for what might be used if all of the US cotton reverted to conventional (non-GM) production methods method, is therefore likely to significantly understate likely usage;

- The widespread adoption of GM IR technology has resulted in 'area-wide' suppression of target pests in maize, cotton and soybean 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 apply insecticides (Hutchison et al, 2010).
- Many farmers have experienced improvements in pest/weed control with GM technology compared to the conventional control methods previously used. If these farmers were to switch back to using conventional techniques, it is likely that most would want to maintain pest/weed control levels obtained with GM traits and therefore some would probably use higher levels of insecticide/herbicide than they did in the pre-GM crop days (eg, as identified by Brookes (2008) relating to IR maize growers in Spain). Nevertheless, the decision to use more pesticide or not would be made according to individual assessment of, for example, the potential benefits (eg, from higher yields) compared to the cost of additional pesticide use.

This methodology has been used by others in relation to analysis of pesticide use change with GM crops in the US such as Sankala and Blumenthal, 2003, Sankala and Blumenthal, 2006, Johnson and Strom, 2006.

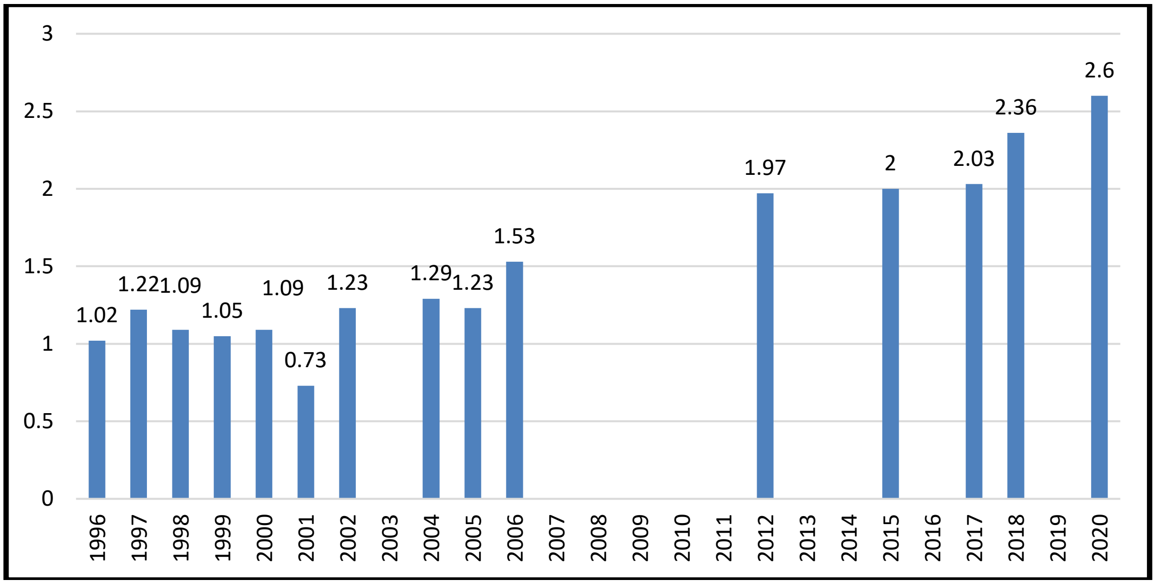
Details of how this methodology has been applied to the 2020 calculations, sources used for each trait/country combination examined and examples of typical conventional versus GM pesticide applications are provided in Appendix 3.

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

a) The US

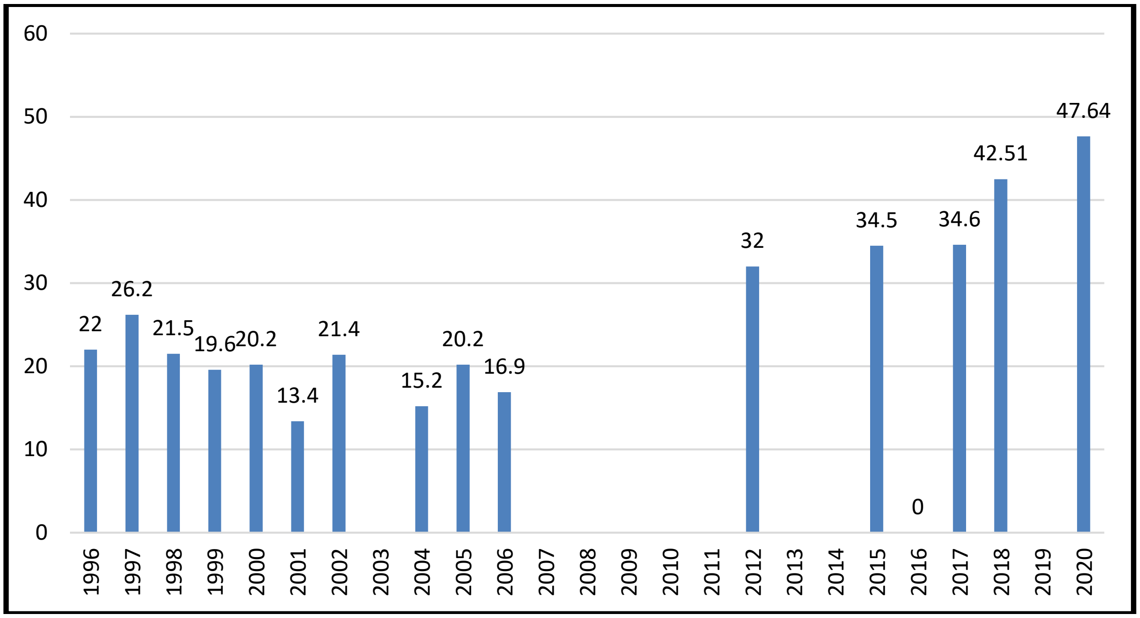
The average amount of herbicide active ingredient (ai) used per hectare on the US soybean crop has been fairly stable for the period to 2006, but has increased since then (Figure 42). The average field EIQ/ha load has followed a broadly similar pattern of change as the amount of active ingredient used (Figure 43).

Figure 42: Average herbicide usage on soybeans in the US 1996-2020 (kg/ha)



Source: USDA NASS. Note - no collection of data in 2003, 2007-2011, 2013, 2014, 2016, 2019

Figure 43: Average herbicide usage on soybeans in the US 1996-2020 (EIQ/ha)



Source: USDA NASS. Note - no collection of data in 2003, 2007-2011, 2013, 2014, 2016, 2019

A comparison of the amount of herbicide active ingredient applied to conventionally grown soybeans (per ha) and GM HT soybeans shows that herbicide ai use on conventional soybeans has also followed a similar pattern of changes in herbicide use with GM HT soybeans. Broadly, the average amount of herbicide active ingredient applied to both types of production was fairly stable up to the mid-2000s (at around 1.1 to 1.3kg/ha for conventional compared to 1.3 to 1.4kg/ha for GM HT soybeans). Since 2006, the average amount of herbicide active ingredient applied to both forms of production has increased in a similar way so that in the last five years the average amount of herbicide active ingredient applied to the GM HT crop (which accounts for 93%-94%

of the total crop) has been in the range 2.5 kg/ha to 3.0 kg/ha compared to the average amount of herbicide active ingredient applied to the conventional crop (which accounts for 6%-7% of the total crop) which has been in the range of 1.75 kg/ha to 2.2 kg/ha[59].

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 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 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.

As a result, over the last 20 years, growers of GM HT crops in the US have been using other herbicides (with different and complementary modes of action) in combination with glyphosate and in some cases adopting cultural practices (eg, reverting back to ploughing) in more integrated weed management systems. In addition, GM HT crops tolerant to other herbicides (often stacked with glyphosate) have also become available from 2016 (notably to dicamba and 2 4 D).

At the macro level, these changes have influenced the mix, total amount and overall environmental profile of herbicides applied to GM HT soybeans (and to cotton, maize and canola) in the last 20 years. For example, in the 2020 US GM HT soybean crop, approximately two-thirds of the crop area was planted to varieties that were tolerant to other herbicides (in addition to tolerance to glyphosate) and even where single tolerance-traited crops were planted, almost all of these crops received an additional herbicide treatment of other active ingredients (notably sulfentrazone, S metolachlor, 2 4 D, metribuzin, metsulfuron and pyrosulfone). This compares with only 14% of the GM HT soybean crop (almost all tolerant to only glyphosate) receiving a treatment of one of the next four most used 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) doubled over this period. It is interesting to note that by 2016, glyphosate accounted for a lower share of total active ingredient use on the GM HT crop (63%) than in 1998 when it accounted for 82% of total active ingredient use, highlighting the continued value to farmers of using glyphosate because of its broad-spectrum activity, in addition to using other herbicides in line with integrated weed management advice. This continues in 2020, with the availability of additional options for weed control via varieties with GM HT tolerance to other herbicides. Whilst alternatives to glyphosate tolerant varieties are available, the vast majority used contain tolerance to glyphosate plus at least one other herbicide.

On the small conventional crop, the average amount of herbicide active ingredient applied also doubled over the period 2006-2020. The increase in the use of herbicides on the conventional soybean crop in the US can also be mainly attributed to the on-going development of weed

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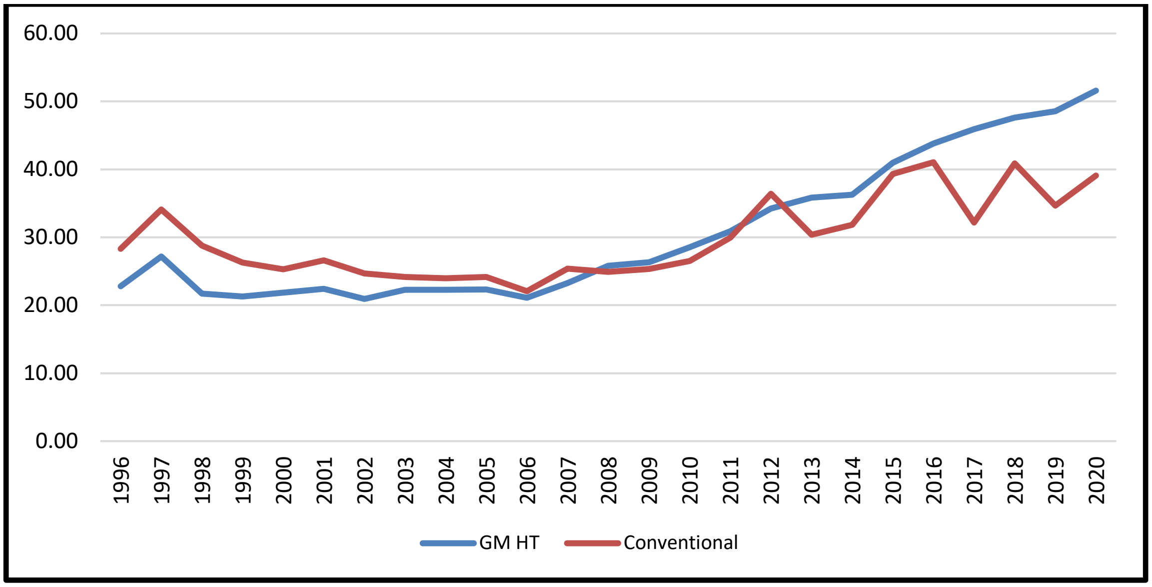
[59] Sources: derived from USDA NASS, University extension services and Kynetec

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.

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 20 years (Figure 43). The average load rating for GM HT soybean crops was lower than the average load rating for conventional soybeans for most of the period up to the mid-2000s, 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.

Figure 44: A comparison of the average EIQ/ha for conventional and GM HT soybeans in the US 1996-2020



Sources: derived from USDA NASS, Kynetec and University extension services

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 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[60]. 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 sources such as USDA NASS and Kynetec, 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 since 2006 are shown in Table 18. 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 18: Average ai use and field EIQs for conventional soybeans 2006-2018 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

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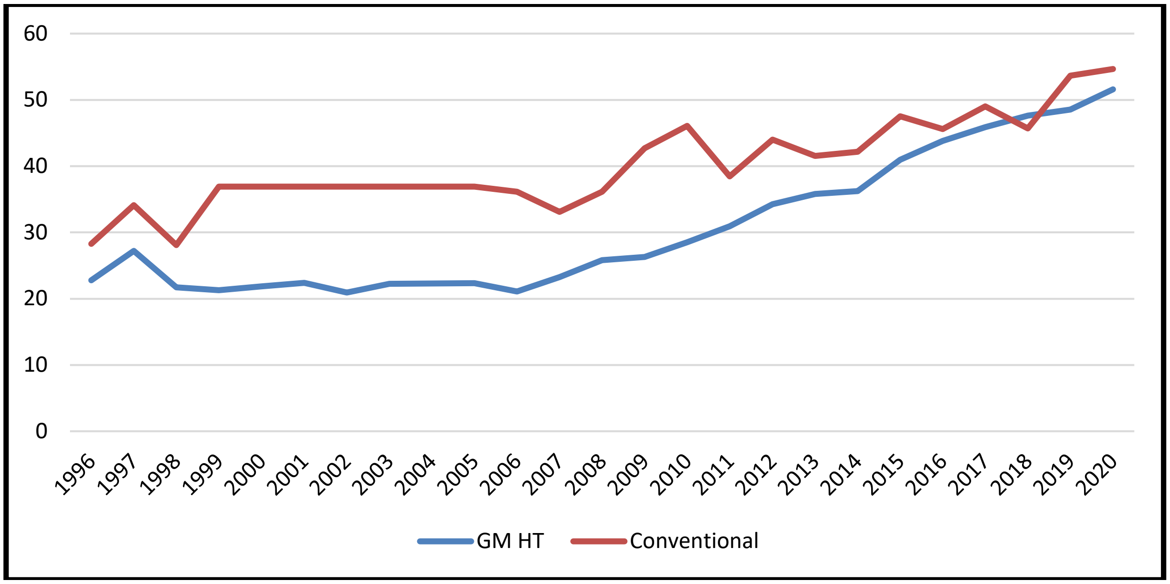
[60] Original analyses by Sankala and Blumenthal (2006) and Johnson and Strom (2008) were based on consultations with extension advisors in over 50 US states. Subsequent years have been updated by the author

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
2016	2.41	45.6
2017	2.57	49.0
2018	2.42	45.7
2019	2.78	53.7
2020	2.78	54.7

Sources: Sankala & Blumenthal (2006), Johnson & Strom (2008) and updated for this research for 2009-2020, based on University Extension Services, Industry, USDA NASS and Kynetec

Using this methodology for comparing conventional versus GM HT soybean herbicide usage in terms of the respective EIQ/ha values, Figure 45 shows that the average EIQ/load per ha for GM HT soybeans has typically been lower than the conventional equivalent, although the gap between the two has narrowed. The average load value for both production systems has also increased between 2006 and 2020).

Figure 45: A comparison of the average EIQ/ha for weed control systems used in conventional soybeans that delivers equal efficacy to weed control systems in GM HT soybeans in the US 2006-2020



Sources: Sankala & Blumenthal (2006), Johnson & Strom (2008) and updated for this research for 2009-2020, based on University Extension Services, Industry, USDA NASS and Kynetec

Aggregating these farm level impacts to the national level:

- In 2020, there was a small net increase in herbicide ai use of 1.7% (1.56 million kg). The EIQ load was lower by 5.3% compared with the conventional (no/low tillage) alternative (ie, if all of the US soybean crop had been planted to conventional soybeans);

- Cumulatively since 1996, there have been savings in both active ingredient usage and the associated environmental impact (as measured by the EIQ indicator) of -1.8% (26.5 million kg) in active ingredient usage and -18.6% for the field EIQ load.

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 adopted[61]. 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;
- 2006-2015, the same values for conventional with 1.32 kg/ai and a field EIQ/ha of 20.88 for GM HT soybeans;
- From 2016, conventional 1.76 kg ai/ha and an average EIQ/ha of 34.9 compared to GM HT with 1.72 kg/ha and 28.02 EIQ/ha.

Based on these values, at the national level[62], in 2020, there was a net decrease in the volume of active ingredient used of 1.7% (-610,000 kg) and a 16.9% decrease in associated environmental impact (as measured by the EIQ indicator: Table 19). Cumulatively since 1997, there has been an 5.1% saving in active ingredient use (3 million kg) and a 20.4% saving in field EIQ/ha indicator value.

Table 19: National level changes in herbicide ai use and field EIQ values for GM HT soybeans in Canada 1997-2018

Year	ai saving (kg)	EIQ saving (units)	% decrease in ai (- = increase)	% EIQ saving
1997	530	20,408	0.03	0.06
1998	25,973	1,000,094	1.8	3.0
1999	106,424	4,097,926	7.4	11.9
2000	112,434	4,329,353	7.4	11.9
2001	169,955	6,544,233	11.1	17.9
2002	230,611	8,879,827	15.7	25.4
2003	276,740	10,656,037	18.5	29.8
2004	351,170	13,522,035	20.4	32.8
2005	373,968	14,399,885	22.2	35.8
2006	84,130	10,191,227	4.8	24.5
2007	75,860	9,167,500	4.5	22.7
2008	96,800	11,726,000	5.6	28.5
2009	103,374	12,521,832	5.2	26.5
2010	113,729	13,776,201	5.4	27.3
2011	97,749	11,840,550	4.4	22.2
2012	119,977	14,533,032	5.0	25.3

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

[62] 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

2013	133,634	16,187,269	5.0	25.3
2014	149,969	18,165,957	3.7	24.1
2015	65,157	12,734,412	1.7	16.7
2016	67,142	13,122,473	1.7	17.1
2017	84,235	16,463,031	1.6	16.1
2018	73,787	14,421,142	1.7	16.3
2019	69,947	13,670,602	1.8	17.3
2020	61,434	12,006,856	1.7	16.9

c) Brazil

Drawing on herbicide usage data from private market research sources (AMIS Global and Kleffmann), plus 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 from the same sources, suggests changes 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 2020 (see Appendix 3) were:

- An average active ingredient usage of 3.1 kg/ha for GM HT soybeans compared to 3.16 kg/ha for conventional soybeans;
- The average field EIQ/ha value for the two production systems were 48.95/ha for GM HT soybeans compared to 54.72/ha for conventional soybeans[63].

Based on the above herbicide usage data, (Table 20):

- In 2020, the total herbicide active ingredient use was 1.7% lower on GM HT crops than it would likely have been if the crop had been conventional. The EIQ/ha environmental load was 10.1% lower than if the crop had been conventional;
- Cumulatively since 1997, there has been a 0.5% increase in herbicide active ingredient use (7.9 million kg). However, there has been a 7.7% reduction in the environmental impact.

Table 20: National level changes in herbicide ai use and field EIQ values for GM HT soybeans in Brazil 1997-2020

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

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[63] 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

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	-2,928,750	-38,073,750	-4.5	-4.1
2008	-2,930,400	-38,095,200	-8.4	-6.5
2009	-3,564,000	-46,332,000	-9.3	-7.2
2010	-4,040,300	-52,523,900	-10.2	-7.9
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	1,806,682	180,421,820	1.7	9.9
2016	1,886,378	188,421,820	1.8	10.2
2017	1,956.742	195,450,242	1.8	10.3
2018	1,999,214	199,692,556	1.7	10.1
2019	2,046,270	203,889,922	1.8	10.1
2020	2,115,113	210,749,397	1.7	10.1

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 2020, the area planted to soybeans was 18.5 million ha. Almost all of this (97%) 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 2020, the estimated average herbicide ai use was 3.59 kg/ha and the average field EIQ was 54.53/ha[64]. Given more than 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 1996-2020 period (some of which may possibly have taken place in the absence of the GM HT technology[65]). Also, the expansion in soybean plantings

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[64] Source: AMIS Global (national herbicide usage data based on farm surveys)

[65] 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

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 for the 2020 alternatives). Based on these, the current GM HT largely no tillage production system, has a marginally lower volume of herbicide ai use (3.59 kg/ha compared to 3.62 kg/ha) than its conventional no tillage alternative. In terms of associated environmental impact, as measured by the EIQ methodology, the GM HT system delivers an 11% improvement (GM HT field EIQ of 54.53/ha compared to 62.04/ha for conventional no/low tillage soybeans). At the national level these reductions in herbicide use[66] are equivalent to:

- In 2020, a 0.7% decrease in the volume of herbicide ai used (0.43 million kg) and a net 11.8% reduction in the associated environmental impact, as measured by the EIQ indicator (120 million EIQ/ha units);
- Cumulatively since 1996, there has been a net increase in herbicide ai use of +0.6% (+7.7 million kg) but a lower (net environmental gain) field EIQ load of 9.4% lower (1.97 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/Kleffmann 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 2020 were:

- 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 2020 were respectively 8.1% higher in terms of active ingredient use (+0.84 million kg), but lower by 14% in terms of associated environmental impact as measured by the EIQ indicator. Cumulatively, since 1999, herbicide ai use has been 6.8% higher (8.5 million kg[67]) whilst the associated environmental

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[66] 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

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

impact, as measured by the EIQ indicator, was 9.3% 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/Kleffmann 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 2020 were:

- Conventional soybeans: average volume of herbicide used 3.04 kg/ha and a field EIQ/ha value of 62.04/ha;
- GM HT soybeans: average volume of herbicide used 3.01 kg/ha and a field EIQ/ha value of 46.23/ha.

Using these values, the level of herbicide ai use and the total EIQ load in 2020 were respectively 0.7% higher in terms of active ingredient use (+29,000 kg), but lower by 24.7% in terms of associated environmental impact as measured by the EIQ indicator. Cumulatively, since 1999, herbicide ai use has been 1.1% higher (704,000 kg) whilst the associated environmental impact, as measured by the EIQ indicator, was 14.2% 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 2020, an 8% increase in the volume of herbicide ai used (365,000 kg) but a net 13.9% 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 7% (+3 million kg) but a net reduction in the field EIQ load of 9%.

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:

- 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/Kleffmann data and typical herbicide programmes for GM HT soybeans and conventional soybeans: see Appendix 3) shows the following:

- Since 1999, the total volume of herbicide ai use has been 9.9% lower (equal to 1.4 million kg of ai) than the level of use if the crop had been conventional;
- The field EIQ load has fallen by 26.4% since 1999 (in 2020 the EIQ load was 31% 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 2004-2012 and then permitted without restriction until 2016[68]) on an annual area of between 2,000 ha and 20,000 ha) shows the following:

- Conventional soybeans: in 2016, 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.

Between 2004 and 2016, the total volume of herbicide ai use has been 0.8% lower (equal to about 21,900 kg of ai) than the level of use if the crop had been conventional. The field EIQ load was also lower by 3.7%.

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 impact[69] has been (Figure 46):

- In 2020 a 0.02% decrease in the total volume of herbicide ai applied (-0.01 million kg) and a 9.3% reduction in the environmental impact (measured in terms of the field EIQ/ha load);

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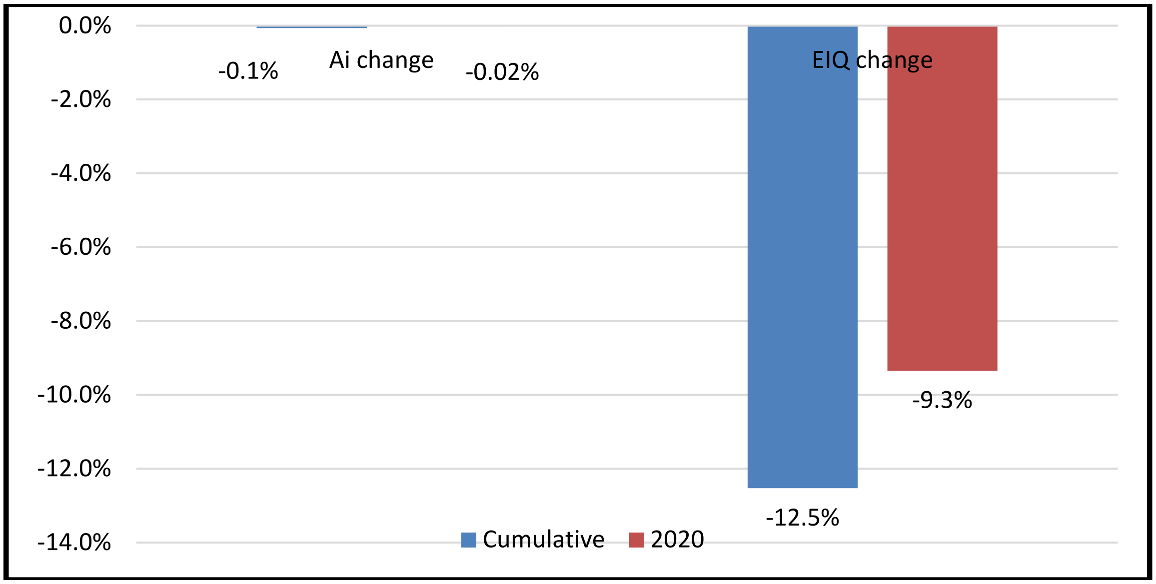
[68] Not permitted for planting since 2017

[69] 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

- Since 1996, 0.1% less herbicide ai has been used (3 million kg) and the environmental impact associated with herbicide use on this global GM HT soybean crop area has fallen (an environmental improvement) by 12.5%.

This analysis takes into consideration changes in herbicide use over the last 15 years, on both GM HT and conventional soybeans, that have occurred to specifically address the issue of weed resistance to glyphosate (and other herbicides) in most regions. Compared to the early 2000s, 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 advantages[70] and in most cases, provides an improved environmental profile compared to the conventional alternative (as measured by the EIQ indicator).

Figure 46: Reduction in herbicide use and the environmental load from using GM HT soybeans in all adopting countries 1996-2020



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/Kleffmann) 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:

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[70] 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

- 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 3.1/ha;

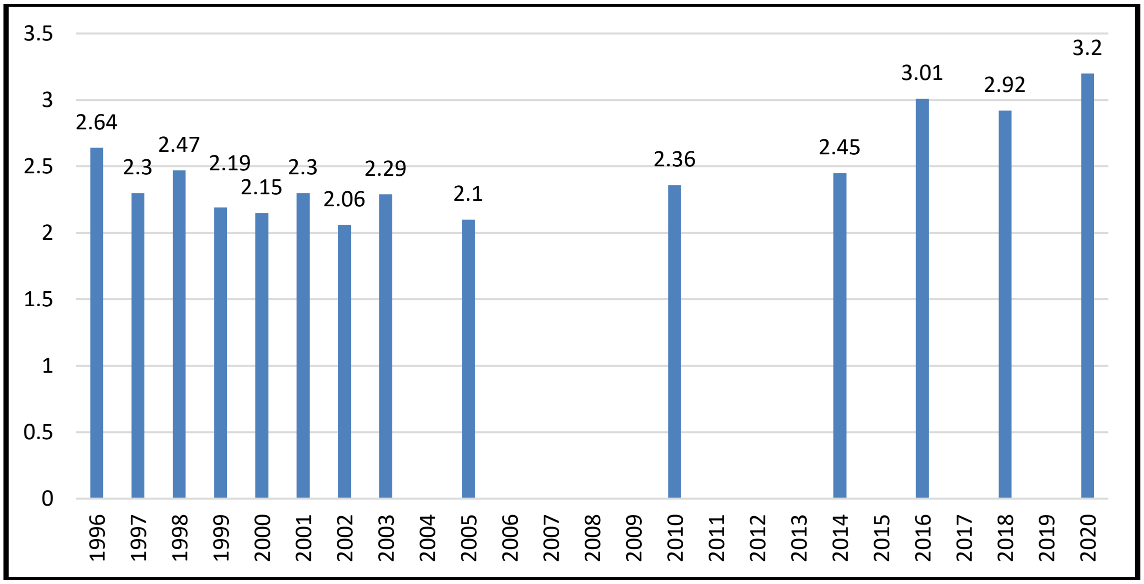
Based on these savings, in 2020, the use of this technology resulted in a reduction of 4.5 million kg of insecticide active ingredient use, equal to 14.6% of total insecticide used on the soybean crops in the four countries. The EIQ saving in 2020 was equal to -27.7%. Over the eight years, the total insecticide active ingredient usage saving has been 23.9 million kg (-9.8%) and the associated environmental impact, as measured by the EIQ indicator fell by 17.8%.

4.1.3 GM Herbicide tolerant (GM HT) maize

a) The US

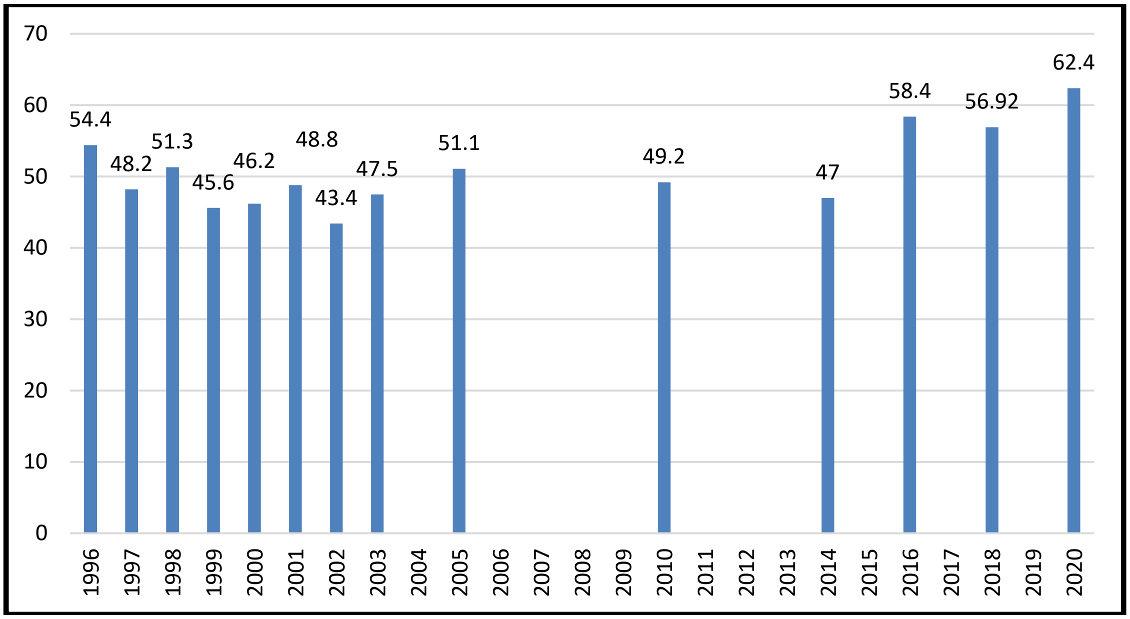
The use of herbicides on the US maize crop has followed similar trends to the use of herbicides on soybeans. The average amount of herbicide active ingredient used on the US maize crop was fairly stable (2.0-2.3 kg/ha) in the period to the mid-2000s before increasing over the next decade to an average of over 3 kg/ha (Figure 47). The average field EIQ/ha load has also followed a 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 (Figure 48);

Figure 47: Average herbicide usage on maize in the US 1996-2020 (kg/ha)



Sources and notes: derived from NASS pesticide usage data. No data collected in 2004, 2006-2009, 2011-2013, 2015, 2017 and 2019

Figure 48: Average herbicide usage on maize in the US 1996-2020 (EIQ/ha)

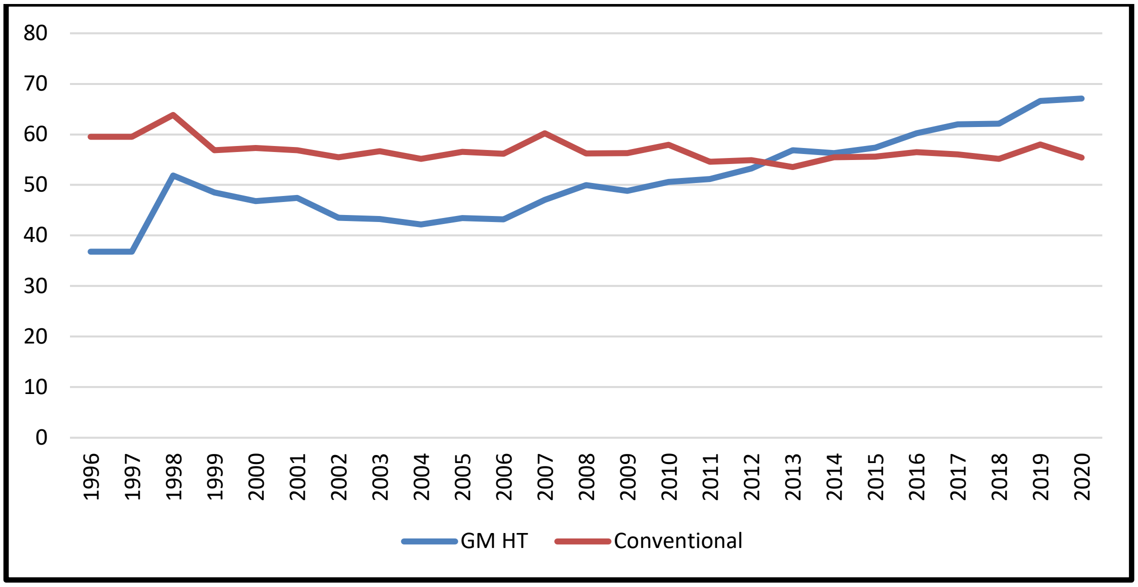


Sources and notes: derived from NASS pesticide usage data. No data collected in 2004, 2006-2009, 2011-2013, 2015, 2017 and 2019

In relation to the use of herbicides on the GM HT and conventional crops, the average amount of herbicide used on the GM HT maize crop was about 0.6 to 0.7 kg/ha lower than the average amount used on conventional crop in the period to about 2007. Since then, the differential between the GM HT crop (which has accounted for more than 85% of the total crop each year since 2013) and small residual 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 residual conventional crop (11% of the total crop in 2020). The average field EIQ/ha value relating to the GM HT crop has typically been about 20/ha units lower than the EIQ/ha load on the conventional crop, although the difference between the average EIQ/ha value in the two production systems has narrowed, with the GM HT average value being higher than the conventional value since 2013 (Figure 49).

The recent increase in ai use and the associated field EIQ/ha for GM HT maize mainly reflects the increasing development of herbicide resistance and the adoption of more integrated 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, S metolachlor and tembotrione as recommended by extension advisors and weed scientists. In addition, as with GM HT soybeans, US farmers have also been able to use an increasing array of stacked-traited GM HT varieties in recent years (eg, combinations of tolerance to the active ingredients glyphosate, glufosinate and 2 4 D).

Figure 49: A comparison of the average EIQ/ha for conventional and GM HT maize in the US 1996-2020



Sources: derived from USDA NASS, Kynetec and University extension services

As with soybeans (see section 4.1.1 a), the comparison data between the GM HT crop and the conventional alternative presented above is 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.

This bias has been addressed, by using the average estimated 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 (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[71]. 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 sources such as USDA NASS and Kynetec, 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 maize since 2007 are shown in Table 21.

Table 21: Average ai use and field EIQs for conventional maize 2007-2018 to deliver equal efficacy to GM HT maize

Year	Ai use (kg/ha)	Field EIQ/ha
2007	3.48	60.22
2008	3.48	56.21
2009	3.78	56.28

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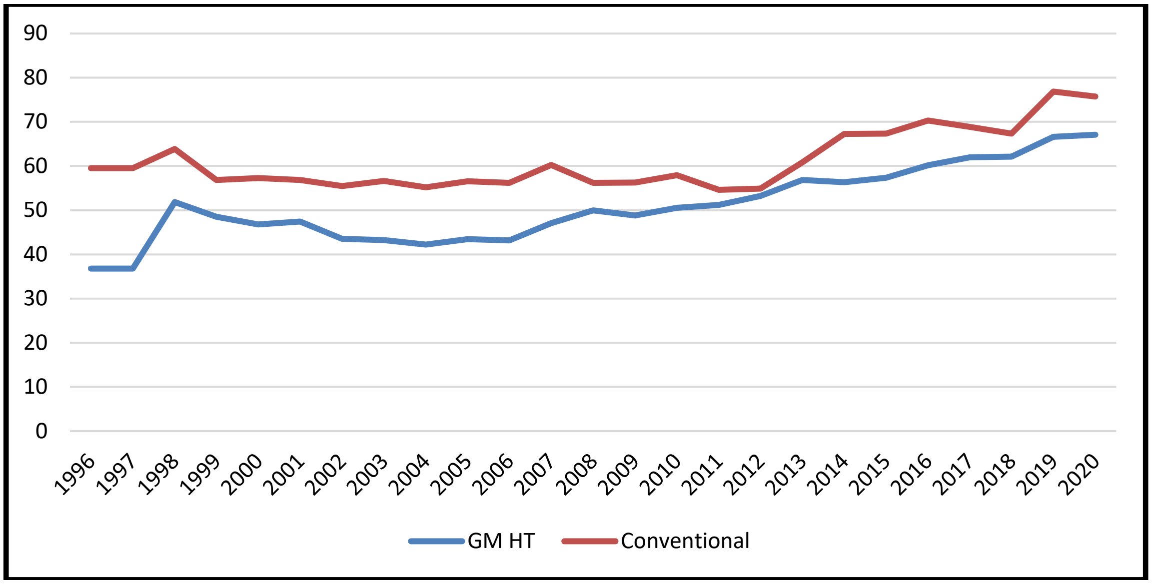
[71] Original analyses by Sankala and Blumenthal (2006) and Johnson and Strom (2008) were based on consultations with extension advisors in over 50 US states. Subsequent years have been updated by the author

2010	3.88	57.95
2011	3.43	54.62
2012	2.91	54.89
2013	3.37	60.84
2014	3.40	67.28
2015	3.41	67.36
2016	3.60	70.32
2017	3.47	68.84
2018	3.38	67.34
2019	3.78	76.86
2020	3.74	75.72

Sources: Sankala & Blumenthal (2006), Johnson & Strom (2008) and updated for this research for 2009-2020, based on University Extension Services, Industry, USDA NASS and Kynetec

Using this methodology for comparing conventional versus GM HT maize herbicide usage in terms of the respective EIQ/ha values, Figure 50 shows that the average EIQ/load per ha for GM HT maize has typically been lower than the conventional equivalent, although the gap between the two has narrowed.

Figure 50: A comparison of the average EIQ/ha for weed control systems used in conventional maize that delivers equal efficacy to weed control systems in GM HT maize in the US 2007-2020



Sources: Sankala & Blumenthal (2006), Johnson & Strom (2008) and updated for this research for 2009-2020, based on University Extension Services, Industry, USDA NASS and Kynetec

Aggregating these farm level impacts to the national level:

- In 2020, the annual saving in the volume of herbicide active ingredient use was 6.4% (8 million kg). The annual field EIQ load on the US maize crop was also lower by 13.9% in 2020;
- The cumulative decrease in active ingredient use since 1997 has been -8.7% (220.3 million kg), and the cumulative reduction in the field EIQ load was 7.4%.

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 information[72] about typical herbicide regimes for conventional and GM HT maize and how these have changed (see Appendix 3 for the current comparison), the key impact findings are:

- In 2020, the herbicide ai/ha load on a GM HT crop has been between 2.81 kg/ha (GM glyphosate tolerant) and 1.97 kg/ha (GM glufosinate tolerant) lower than the conventional maize equivalent crop (average herbicide ai use at 2.97 kg/ha);
- The field EIQ/ha values for GM glyphosate and GM glufosinate tolerant maize are respectively 54.44/ha and 43.38/ha compared to 67.91/ha for conventional maize;
- At the national level in 2020 (based on the plantings of the different production systems), the reductions in herbicide ai use and the total field EIQ load were respectively 5.8% (241,000 kg kg) and 19.8%;
- Cumulatively since 1997, total national herbicide ai use has fallen by 8% (6.6 million kg) and the total EIQ load has fallen by 15.9%.

c) South Africa

Drawing on herbicide usage data from AMIS Global/Kleffmann and industry level sources that compare typical weed control practices for conventional and GM HT maize in South Africa), the impact of using GM HT technology in the South African maize crop has been:

- On a per hectare basis in 2020 there has been a 0.11 kg increase in the amount of herbicide active ingredient used but a decrease (environmental improvement) in the average field EIQ of 6.99/ha (GM HT crop average of 2.33 kg ai/ha and field EIQ/ha value of 39.46/ha, conventional 2.22 kg ai/ha and average EIQ/ha value 46.45/ha);
- In 2020, at the national level, the amount of herbicide used was 230,000 kgs (+3.8%) higher 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 12% lower;
- Cumulatively since 2003, total national herbicide ai use has fallen by 1.1% (1.4 million kg) and the total EIQ load has fallen by 7.8%.

d) Argentina

Using a combination of AMIS Global/Kleffmann 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 2020 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

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

recent years the difference between the two systems has narrowed. In 2020, 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 2020 was 2.91 million kg (+12.9%). Since 2004, there has been a net increase in usage of 5.5% (12.8 million kg);
- In terms of the field EIQ load, the reduction in 2020 was 2.5% and over the period 2004-2020, the EIQ load factor fell by 4%.

e) Brazil

Brazil first used GM HT maize commercially in 2010, and in 2020, the area planted to seed containing this trait was 16.4 million ha. Drawing on a combination of sources (AMIS Global/Kleffmann, 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 2020 was 2.81 kg/ha and 48.86/ha respectively. This compared with conventional maize with herbicide active ingredient use of 2.81 kg/ha and a field EIQ rating of 56.45/ha;
- In 2020, the use of GM HT technology resulted no change in the use of herbicide active
- ingredient but a reduction in the EIQ rating of 11.2%;
- Cumulatively (2010-2020), the herbicide active ingredient usage saving has been 1.4% (8.1 million kg), with an EIQ load reduction of 9.3%.

f) Uruguay

GM HT maize was first used in Uruguay in 2011, and in 2020 was planted on 90% of the maize crop (126,000 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 increase in herbicide ai use on the maize crop of 171,000 kg of active ingredient (+6.1%) but a 4% improvement in the aggregate field EIQ/ha load.

g) Philippines

GM HT maize was first used in the Philippines in 2006, and in 2020 was planted on 27% of the total maize crop (686,000 ha of GM HT maize). Based on Kleffmann and Kynetec data and unpublished survey work amongst farmers in 2017 by the authors, this points to:

- The average amount of herbicide active use and associated field EIQ/ha rating for GM HT maize in 2020 was 1.92 kg/ha and 32.93/ha respectively. This compared with conventional maize with herbicide active ingredient use of 1.9 kg/ha and a field EIQ rating of 43.41/ha;
- In 2020, the use of GM HT technology resulted a marginal 1% (10,000 kg) increase in herbicide active ingredient use but a reduction in the EIQ rating of 24%;
- Cumulatively (2006-2020), the herbicide active ingredient usage saving has been marginally higher (+1% - 0.1 million kg), with an EIQ load reduction of 19%.

h) *Vietnam*

GM HT maize was first used in 2015, and in 2020 was planted on 9.7% of the total maize crop (92,000 ha of GM HT maize – all as stacked seed with both GM HT and GM IR traits).

Based on Kleffmann and Kynetec data and analysis by the author in 2017 and 2020, this shows that:

- The average amount of herbicide active ingredient used and associated field EIQ/ha rating for GM HT maize in 2020 was 2.08 kg/ha and 37.99/ha respectively. This compared with conventional maize with herbicide active ingredient use of 2.88 kg/ha and a field EIQ rating of 59.74/ha;
- Cumulatively (2015-2020), the herbicide active ingredient usage saving has been 2.2% (0.25 million kg), with an EIQ load reduction of 2.9%.

i) *Colombia*

GM HT maize was planted on 109,000 ha (58% of the commercial total crop) in 2020. Drawing on analysis in Brookes (2020), which also draws on a study by Mendez et al (2011) and surveys of maize growers in 2015 and 2017 by Celeres:

- The average amount of herbicide active use and associated field EIQ/ha rating for GM HT maize in 2020 was 2.07 kg/ha and 40.98/ha respectively. This compared with conventional maize with herbicide active ingredient use of 2.51 kg/ha and a field EIQ rating of 59.05/ha;
- In 2020, the use of GM HT technology resulted a reduction in the use of herbicide active ingredient of 48,800 kg (-26%) and a reduction in the EIQ rating of 26%;
- Cumulatively (2015-2020), the herbicide active ingredient usage saving has been 15% (367,000 kg), with an EIQ load reduction of 26%.

j) *Other countries*

GM HT maize was also grown in Paraguay (472,000 ha in 2020). Analysis of the environmental impact associated with changes in herbicide use on this crop has not been possible due to a lack of data.

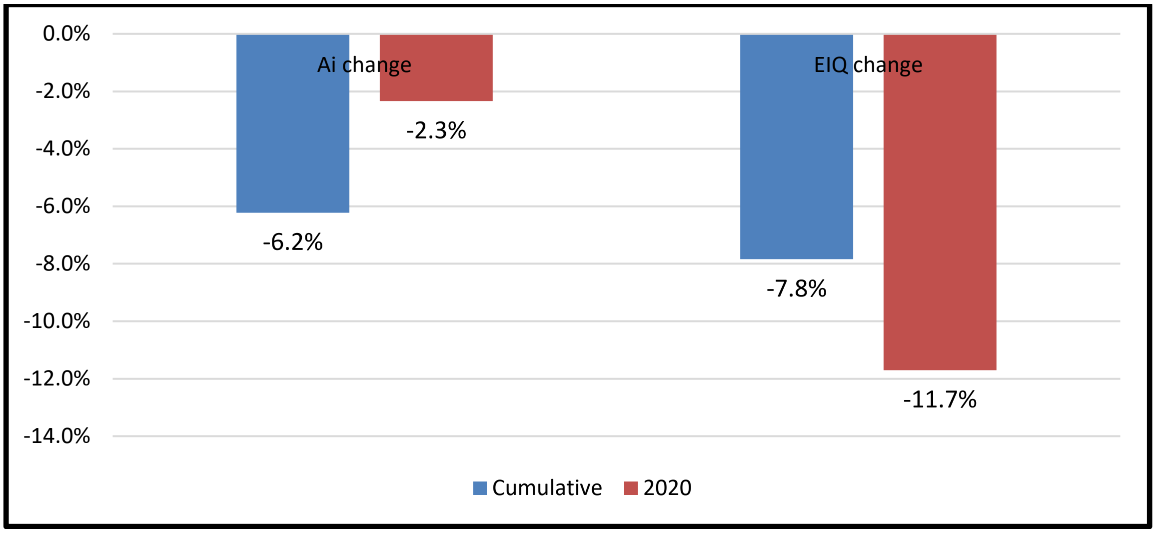
k) *Summary of impact*

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 51). More specifically:

- In 2020, total herbicide ai use was 2.3% lower (5.1 million kg) than the level of use if the total crop had been planted to conventional varieties. The EIQ load was also lower by 11.7%;
- Cumulatively since 1997, the volume of herbicide ai applied is 6.2% lower than its conventional equivalent (a saving of 224 million kg). The EIQ load has been reduced by 7.8%.

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 51: Reduction in herbicide use and the environmental load from using GM HT maize in adopting countries 1997-2020

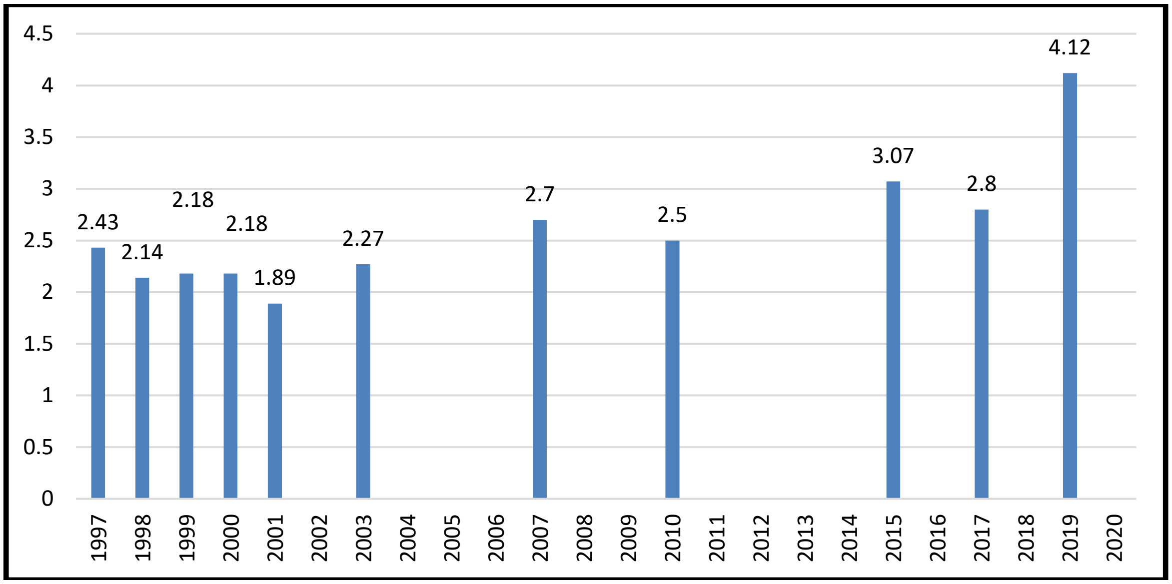


4.1.4 GM HT Herbicide tolerant (GM HT) cotton

a) The US

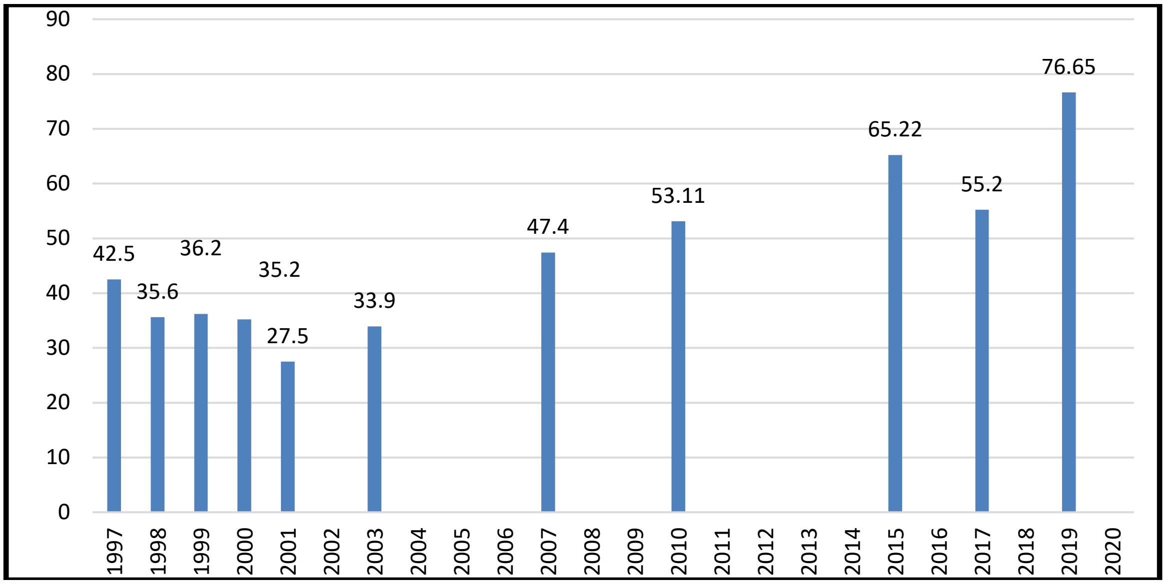
The use of herbicides on the US cotton crop has followed similar trends to the use of herbicides on soybeans and maize. The average amount of herbicide active ingredient used on the US cotton crop was reasonably stable (1.9-2.4 kg/ha) in the period to the mid-2000s before increasing over the next decade to an average of over 3 kg/ha (Figure 52). The average field EIQ/ha load has also followed a 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 (Figure 53).

Figure 52: Average herbicide usage on cotton in the US 1997-2019 (kg/ha)



Sources and notes: USDA NASS pesticide usage data (no data collected in 2002, 2004, 2006, 2008, 2009, 2011-2014, 2016, 2018, 2020), Although data was also collected in 2005, these results are not included because they are inconsistent with all other data

Figure 53: Average herbicide usage on cotton in the US 1997-2019 (EIQ/ha)

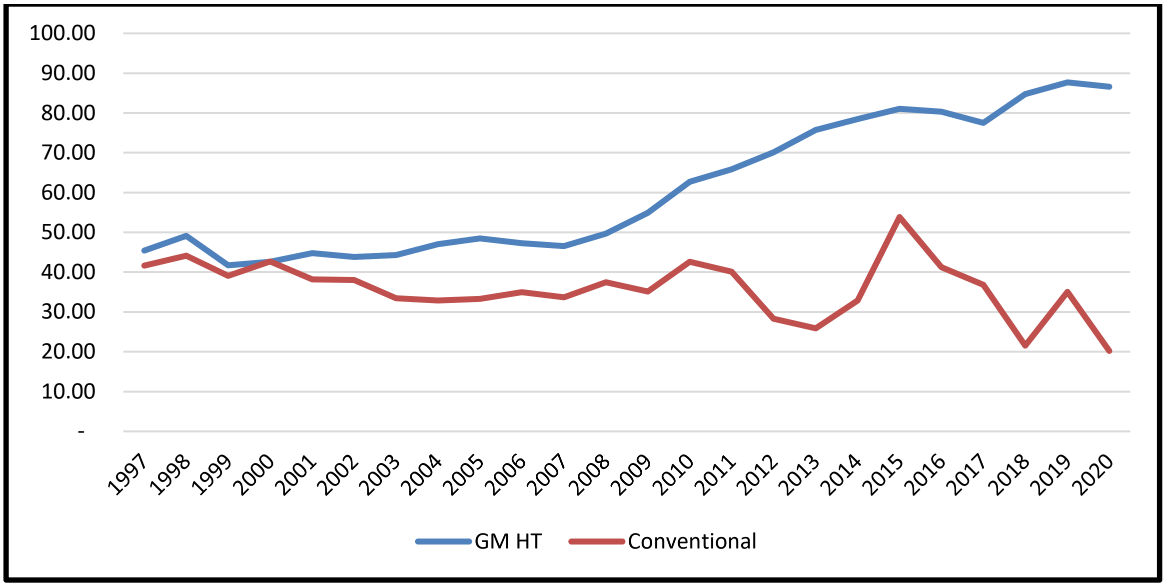


Sources and notes: USDA NASS pesticide usage data (no data collected in 2002, 2004, 2006, 2008, 2009, 2011-2014, 2016, 2018, 2020), Although data was also collected in 2005, these results are not included because they are inconsistent with the data for other years

Comparing the use of herbicides on the GM HT and conventional crops, the average amount of herbicide used on the GM HT crop has been consistently higher than the average amount used on the conventional 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 higher than conventional cotton by an increasing amount (Figure 54).

As in the case of GM HT soybeans and maize, the increase in ai use and the associated field EIQ/ha for GM HT cotton since the mid-2000s largely reflects the increasing development of herbicide resistance and the adoption of more integrated weed management practices designed to address the issue of weed resistance to glyphosate (see section 4.1.9 for more detailed discussion). 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, diuron, flumioxazin and paraquat). 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, pyrithiobic, pendimethalin and diuron). This shows that US cotton farmers now make increasing use of additional herbicides with different modes of action for managing weed resistance (to glyphosate). Many are also making increasing use of GM HT crops tolerant to other herbicides such as to glufosinate (crops with stacked traits conveying tolerance to both glyphosate and glufosinate. For example, about a third of the GM HT cotton area in the US was probably using glufosinate for ‘over the top’ weed control by 2016 compared to 10% of the crop five years earlier.

Figure 54: A comparison of the average EIQ/ha for conventional and GM HT cotton in the US 1997-2020



Sources: derived from USDA NASS, Kynetec and University extension services

As with soybeans and maize discussed above, the comparison data between the GM HT crop and the conventional alternative presented above is 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. This is particularly relevant in the case of the US cotton crop because much of the residual conventional crop area involves 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 technology

This bias has been addressed, by 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[73]. 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 sources such as USDA NASS and Kynetec, 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 cotton since 2006 are shown in Table 22.

Table 22: Average ai use and field EIQs for conventional cotton 2006-2020 to deliver equal efficacy to GM HT cotton

Year	ai use (kg/ha)	Field EIQ/ha
2006	3.75	65.57
2007	3.88	63.75
2008	4.26	76.10
2009	3.84	69.61
2010	4.07	72.32
2011	4.48	77.35
2012	4.54	78.31
2013	4.96	79.25
2014	4.71	76.07
2015	4.82	83.03
2016	4.57	85.42
2017	4.41	78.83
2018	3.89	76.34
2019	4.49	87.30
2020	4.50	90.28

Sources: Sankala & Blumenthal (2006), Johnson & Strom (2008) and updated for this research for 2009-2020, based on University Extension Services, Industry, USDA NASS and Kynetec

Using this methodology for comparing conventional versus GM HT maize herbicide usage in terms of the respective EIQ/ha values, Figure 55 shows that the average EIQ/load per ha for GM HT maize has typically been lower than the conventional equivalent, although the gap between the two has narrowed.

Applying this basis for comparing herbicide regimes for conventional and GM HT cotton at the national level, the impact of using the GM HT technology in 2020 resulted in a 2.4% increase in the amount of herbicide use (0.38 million kg) but a 3.8% decrease in the associated environmental impact, as measured by the EIQ indicator. Cumulatively since 1997, there have been savings in herbicide use of 6.5% for ai use (25.7 million kg) and a 5.9% reduction in the associated environmental impact, as measured by the EIQ indicator.

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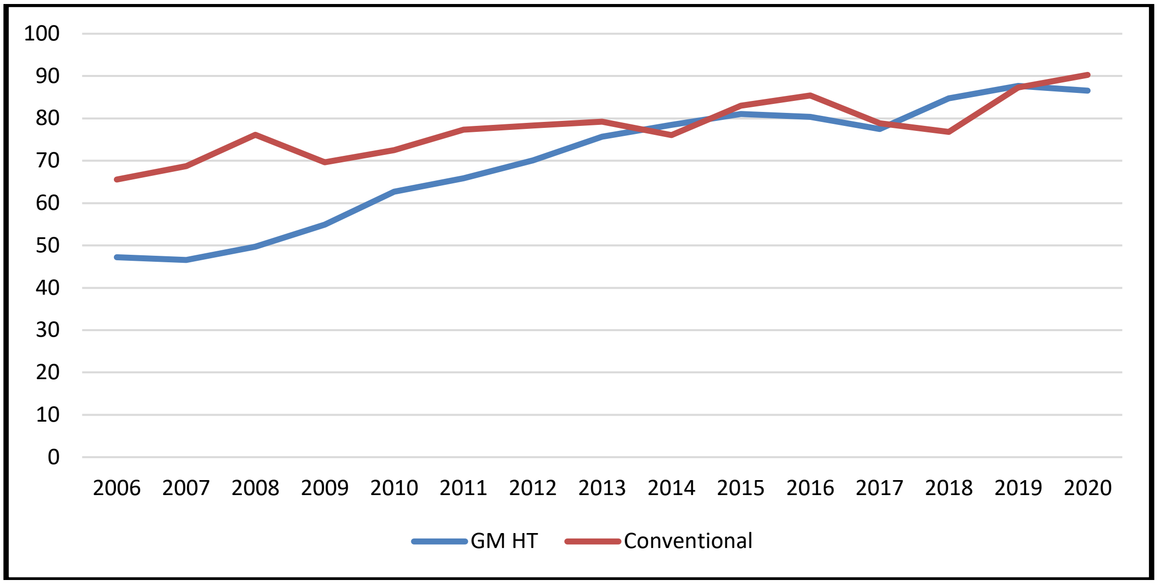
[73] Original analyses by Sankala and Blumenthal (2006) and Johnson and Strom (2008) were based on consultations with extension advisors in over 50 US states. Subsequent years have been updated by the author

Figure 55: A comparison of the average EIQ/ha for weed control systems used in conventional cotton that delivers equal efficacy to weed control systems in GM HT maize in the US 2007-2020



Sources: Sankala & Blumenthal (2006), Johnson & Strom (2008) and updated for this research for 2009-2020, based on University Extension Services, Industry, USDA NASS and Kynetec

b) Australia

Drawing initially on information from the University of New England study from 2003[74], and then subsequent analysis of typical herbicide treatment programmes for GM HT and conventional cotton (based on industry (eg, Monsanto, 2016) and extension 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 2020, 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 crop[75];
- 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. In 2020, the average field EIQ/ha for GM HT cotton was 90/ha compared to 143/ha for the conventional cotton equivalent;

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[74] Doyle et al (2003)

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

- Based on the above data, at the national level, in 2020, herbicide ai use has been 29.5% lower (-617,000 kg of ai) than the level expected if the whole crop had been planted to conventional cotton cultivars. The total field EIQ load was 37% lower;
- Cumulatively since 2000, total national herbicide ai use has fallen by 20.5% (6.5 million kg) and the total EIQ load decreased by 26.7%.

c) South Africa

Using industry level sources that compare typical weed control programmes 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 2020, 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 2020 was 162 kg (0.6%) 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 0.5% (3,800 kg), but the total EIQ load fell by 9.4%. 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 2020, all of the cotton crop (450,000 ha) used seed containing this trait.

Based on industry and extension sources relating to typical weed control programmes for GM HT and conventional cotton (GM HT 4.06 kg ai/ha and EIQ/ha of 63.96/ha, conventional 4.72 kg ai/ha and EIQ/ha 78.40/ha), the impact of using this technology on herbicide use and the associated environmental impact has been:

- In 2020, the national level reduction in the amount of herbicide applied to the cotton crop was 296,000 kg (-16%) 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 26% (-6.2 million kg). The field EIQ rating associated with herbicide use on the Argentine cotton crop fell 27% over the same period.

e) Colombia

GM HT cotton was first grown commercially in Colombia in 2002, and in 2020, 56% of the cotton crop (4,825 ha of GM HT cotton) used seed containing this trait.

Drawing on analysis in Brookes (2020), which also draws on surveys of cotton growers in 2015 and 2017 by Celeres:

- The average amount of herbicide active use and associated field EIQ/ha rating for GM HT cotton in 2020 were 1.79 kg/ha and 28.03/ha respectively. This compared with conventional cotton with herbicide active ingredient use of 2.305 kg/ha and a field EIQ rating of 38.21/ha;

- In 2020, the use of GM HT technology resulted a reduction in the use of herbicide active ingredient of 2,470 kg (-12%) and a reduction in the EIQ rating of 15%;
- Cumulatively (2006-2020), the herbicide active ingredient usage saving has been 7.7% (47,700 kg), with an EIQ load reduction of 6.6%.

f) Other countries

Cotton farmers in Mexico, Brazil and Paraguay have also been using GM HT technology since 2005, 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.

g) Summary of impact

In 2020, the overall effect of using GM HT cotton technology (Figure 56) in the adopting countries has been a reduction in herbicide ai use[76] of 2.8% and a decrease in the total environmental impact of 8.6%. Cumulatively since 1997, herbicide ai use fell by 8.5% (-38.4 million kg) and the associated environmental impact fell by 8.8%.

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 2020 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.

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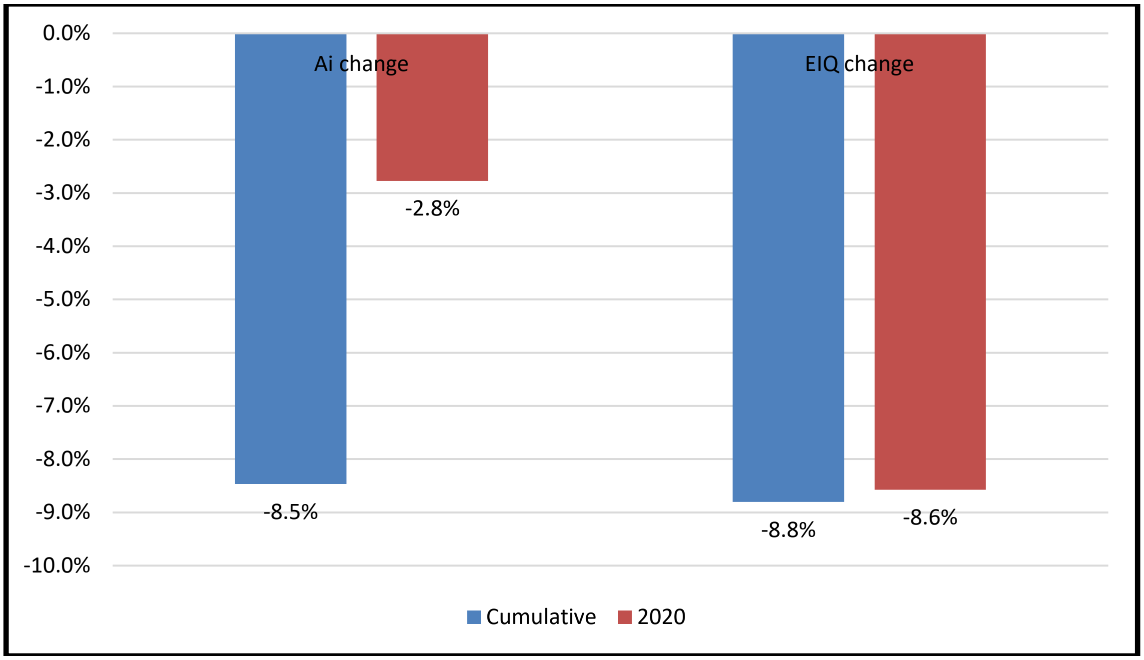
[76] Relative to the herbicide use expected if all of the GM HT area had been planted to conventional cultivars, using the same tillage system and providing the same level of weed control as delivered by the GM HT system

Figure 56: Reduction in herbicide use and the environmental load from using GM HT cotton in the US, Australia, Argentina, Colombia and South Africa 1997-2020



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 (sources: Sankala and Blumenthal (2003 & 2006), Johnson and Strom (2008), university and private extension advisory services, industry analysts and Kynetec), the changes in herbicide use and resulting environmental impact arising from adoption of GM HT canola in the US since 1999[77] are summarised in Figure 57 and Figure 58. These show 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.

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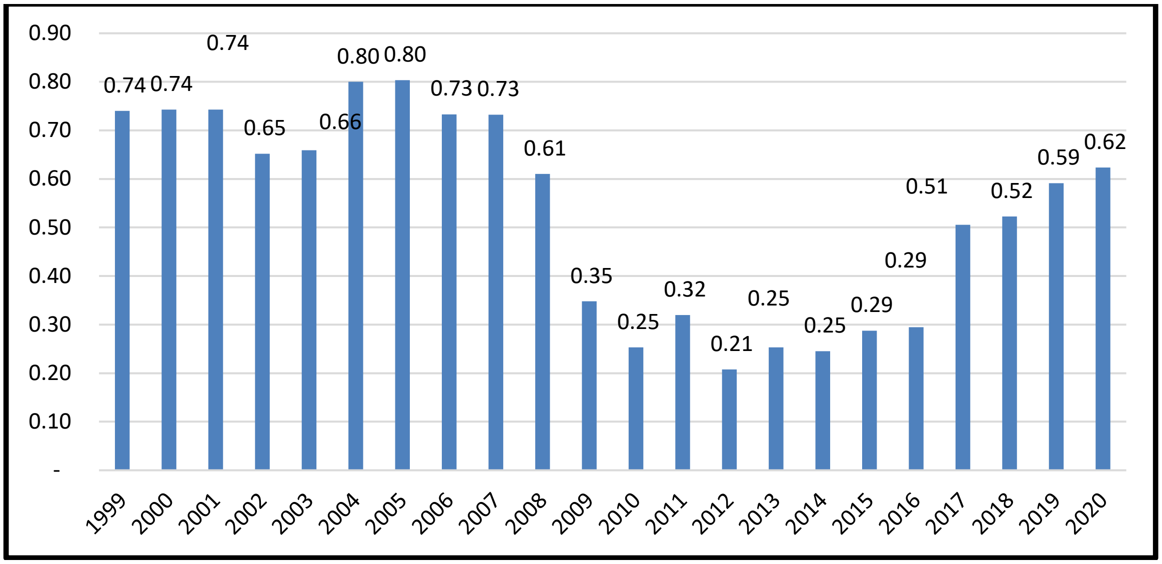
[77] The USDA pesticide usage survey does not include coverage of canola

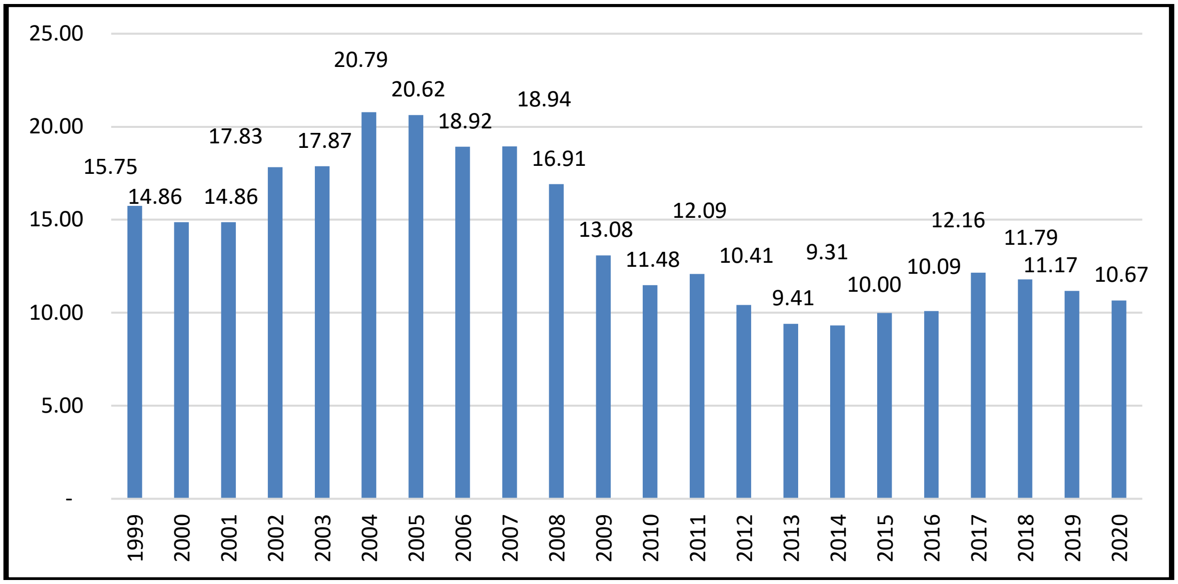
Figure 57: Average active ingredient differences conventional versus GM HT canola US 1999-2020



Sources: derived from Sankala & Blumenthal (2003 & 2006), Johnson & Strom (2008), university and private sector extension advisors, industry analysts and Kynetec

Note: Values shown are weighted average (by area planted) of glyphosate tolerant and glufosinate tolerant GM HT canola compared to conventional canola

Figure 58: Average EIQ/ha differences conventional versus GM HT canola US 1999-2020



Sources: derived from Sankala & Blumenthal (2003 & 2006), Johnson & Strom (2008), university and private sector extension advisors, industry analysts and Kynetec

Note: Values shown are weighted average (by area planted) of glyphosate tolerant and glufosinate tolerant varieties

The reduction in the volume of herbicides used was equal to 429,000 kg of active ingredient (-55.9%) in 2020. In terms of the EIQ load, this had fallen by 45.4% 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 38% (-5.1 million kg ai), and the EIQ load reduced by 46.6%.

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 are planted to non-GM varieties[78]. As in the US, in 2020, in terms of active ingredient use, GM HT canola tolerant to glyphosate uses marginally more (0.01 kg/ha) and GM HT canola tolerant to glufosinate uses 0.35 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 (in 2020, 14/ha for GM glyphosate tolerant canola, 11.2/ha for GM glufosinate tolerant canola and 14.52/ha for conventional canola);
- On the basis of these comparisons with conventional canola, the reduction in the volume of herbicide used was 1.6 million kg (a reduction of 21.7%) in 2020. Since 1996, the cumulative reduction in usage has been 20% (26.9 million kg);
- In terms of the field EIQ load, the reduction in 2020 was 37% and over the period 1996-2020, the EIQ load factor fell by 30%.

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 (sources: Monsanto Australia (2016), Hudson and Richards (2014a and 2014b) to reflect changes in weed management practices (notably for weed resistance management). In 2020, the average[79] 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 0.29 million kg of active ingredient (a 9% saving across the total canola crop) and an 12.3% reduction in the associated environmental impact of herbicide use (as measured by the EIQ indicator) on the 2020 Australian canola crop. Since 2008, the total herbicide active ingredient saving arising from use of GM HT canola has been about 2.12 million kg of active ingredient (-5.5%), with the EIQ load falling by 7.6%.

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[78] Herbicide tolerant by a non-GM process, tolerant to the imidazolinone group of herbicides

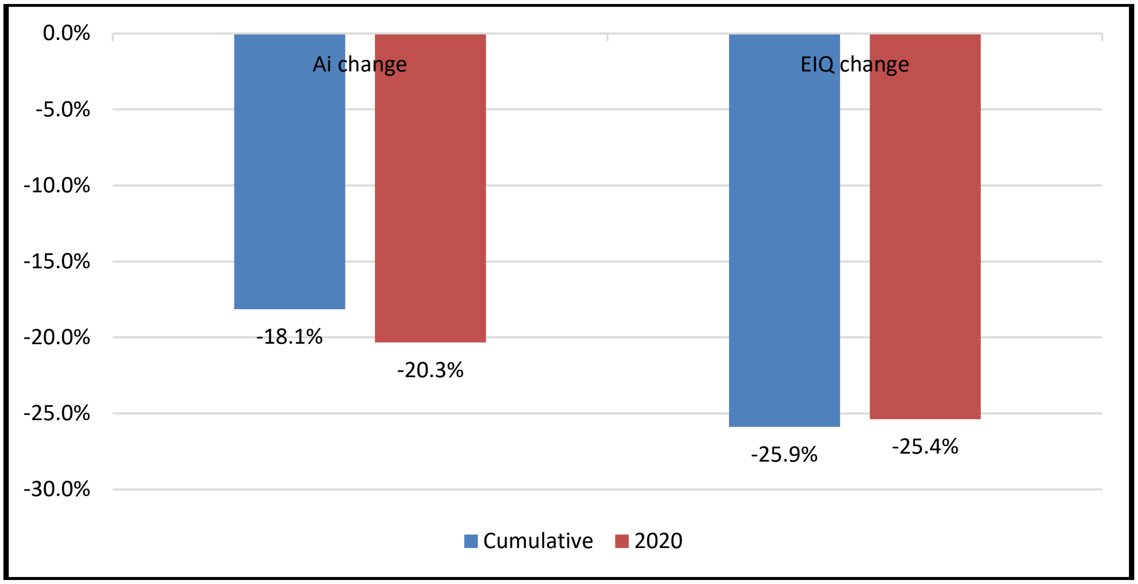
[79] Weighted by sales of seed between TT, 'Clearfield' and GM HT

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 59). More specifically:

- In 2020, total herbicide ai use was 20% lower (2.3 million kg) than the level of use if the total crop had been planted to conventional varieties. The EIQ load was also lower by 25.4%;
- Cumulatively since 1996, the volume of herbicide ai applied was 18.1% lower than its conventional equivalent (a saving of 34.1 million kg). The EIQ load had been reduced by 25.9%.

Figure 59: Reduction in herbicide use and the environmental load from using GM HT canola in the US, Canada and Australia 1996-2020



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 2020 accounted for all of the crop (462,280 ha). In terms of weed control, the use of this technology has resulted in a switch in use from a number of selective herbicides plus some hand/mechanical weeding to a glyphosate-based herbicide weed control programme. Drawing on evidence from a combination of sources (Khan 2008, Stachler et al, 2012, university extension services, industry analysts and the Kynetec dataset on pesticide use), the analysis below summarises the environmental impact.

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. For several subsequent years, the average amount of herbicide applied to the GM HT crop has increased as farmers increasingly adopted 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 in 2007, 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, revising/updating the conventional baseline weed control practices that would likely be required in 2020 to deliver the same level of weed control in a conventional crop as obtained in a GM HT crop, the comparison of herbicide regimes suggests that the GM HT crop would use marginally more herbicide, in terms of amount of active ingredient applied and would have a slightly higher EIQ/ha value than the conventional equivalent (GM HT 3.57 kg ai/ha and a field EIQ/ha value of 62.65, compared to conventional 3.42 kg ai/ha, with a field EIQ/ha value of 62.52). Taking these changes into consideration, in 2020, the use of GM HT sugar beet resulted in an increase in the amount of herbicide active ingredient used of 4% (69,000 kg) and a net increase in the associated EIQ value of 0.2%. 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 alternative[80], there has been a net decrease in the amount of herbicide active ingredient used of 0.76 million kg (-4%) and a net reduction in the environmental load associated with herbicide use, as measured by the EIQ indicator of 15.5%.

GM HT sugar beet is also planted on a small area (17,400 ha in 2020) 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 across the whole crop has fallen (Figure 60).

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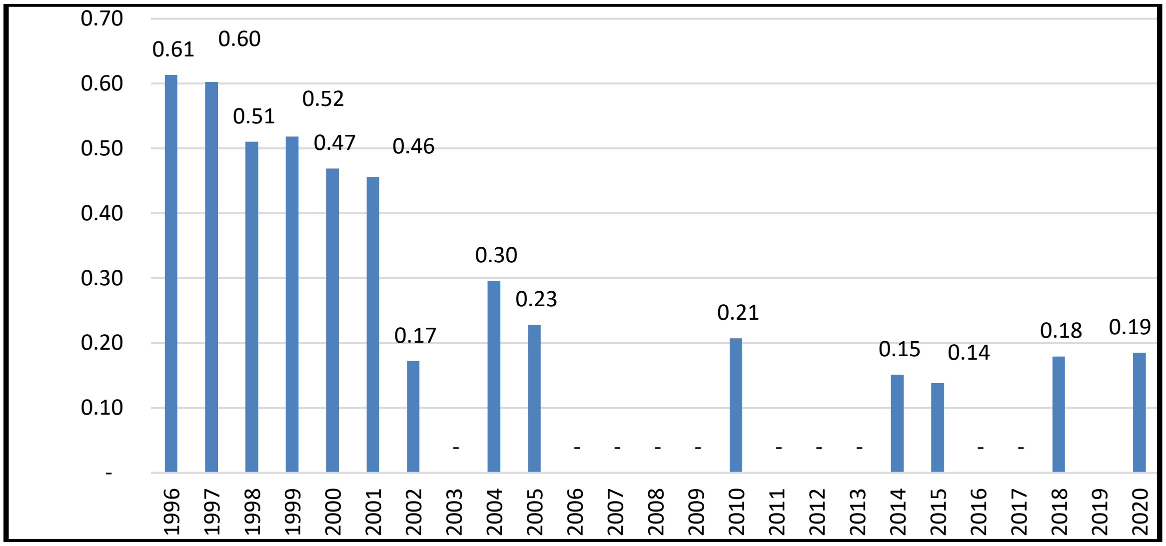
[80] Which in effect is a largely hypothetical alternative given that almost all of the crop uses GM HT technology

Figure 60: Average insecticide use on maize 1996-2020 (kg active ingredient/ha)



Source: USDA NASS (no surveys of insecticide use in 2003, 2006-2009, 2011-2013, 2016-2017, 2019)
Note This relates to the average usage per ha of crop that used insecticides (eg, in 1996, this was estimated to be on about a third of the crop, and in 2020 was about 17% of the crop

During this 25-year period the average amount of insecticide used has fallen on both the conventional and GM IR crop, although the level of insecticide ai use on the GM IR crop has been consistently lower than the average usage level on the conventional crop.

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, historically, a maximum of about 10% of the crop was treated with insecticides for the control of stalk boring pests each year and about 30% of the US maize area treated with insecticides for corn rootworm control. 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 15 years. This reflects the growing preference by farmers for sowing maize seed that has been treated with the insecticides clothiandin and thiamethoxam and is unrelated to the adoption of GM IR technology;
- The first users of the GM IR technology have tended to be 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, as adoption levels have increased, using the recorded level of insecticide use on the small conventional crop as a base for making comparisons with insecticide use on the GM IR area is likely to understate the insecticide savings associated with the adoption of the GM IR technology, because the limited number of conventional farmers are increasingly likely to be in locations where pest pressure levels (for the pests that the GM IR technology targets) are lower than the levels of pest pressure in the majority of the country and hence are likely to use relatively low levels of insecticides;

- 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 applications (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 sources such as extension services, USDA NASS data, private pesticide usage databases (eg, Kynetec) and relevant literature (eg, Carpenter & Gianessi (1999)). Drawing on these sources we identified average usage of insecticides for the control of stalk boring pests and rootworm at about 0.6 kg /ha. The corresponding field EIQ/ha value was about 30/ha.

In the early years of adoption, these active ingredient and field EIQ saving were then applied to the maximum of the area historically receiving insecticide spray treatments for stalk boring pests and corn rootworm (about a third 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 have been applied in years since the early 2000s has been based on the difference between this maximum treated area (33% of total crop) and the estimated total base crop area recorded as having received insecticide treatments (sources USDA NASS and Kynetec)

Based on this approach, at the national level, the use of GM IR maize has resulted in a saving in the area treated with insecticides of about 5.5 million ha in 2020 and a saving in the volume of insecticide ai use of 3.3 million kg ai (a 50% saving). The annual field EIQ load also fell by 50% in 2020. Since 1996, the cumulative decrease in insecticide ai use targeted at these pests has been 37% (60.8 million kg), and the cumulative reduction in the field EIQ load has been 38%.

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 required[81], 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

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[81] 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

Canadian maize area in any subsequent year, the cumulative reduction in insecticide ai use targeted at stalk boring pests has been 914,500 kg (-89%). In terms of environmental load, the total EIQ/ha load has fallen by 62%[82].

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 (2003)), 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. This analysis has been subsequently checked and updated (based on extension advice and industry analyst information) to reflect changing pest control practices and products available for control, with the latest estimated impacts drawn from Brookes (2019). Overall, the adoption of GM IR maize technology, has led to a significant net decrease in both the volume of insecticide used and the associated field EIQ/ha load[83]. More specifically:

- The volume of total maize insecticide ai use was 37.5% lower than the level would probably have been if the entire crop had been conventional in 2020 (-33,250 kg). Since 1998 the cumulative saving (relative to the level of use if all of the crop had been conventional) has been 745,750 kg of insecticide ai (a 37% decrease);
- The field EIQ/ha load has fallen by 21% since 1999. In 2020, the field EIQ load was 20% 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 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 (derived from extension advisors and industry analysts):

- 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);

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

[83] The average volume of insecticide ai use saved has been 0.96 kg/ha with an average field EIQ of 26/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 2020, 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 75.7% (2.6 million kg ai).

f) Brazil

The GM IR maize area in Brazil, in 2020, was 18 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/ha[84]. 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 million kg of insecticide active ingredient saving in 2020. This represents a 60% reduction in the amount of insecticide used and an 80% reduction in the associated environmental impact associated with insecticide use, as measured by the EIQ indicator. Cumulatively, the ai and field EIQ savings have been respectively 56% and 75% lower than they would otherwise have been if this technology had not been used (a saving of 19.9 million kg of ai).

g) Colombia

GM IR maize was planted on 96,250 ha (51% of the commercial total crop) in 2020. Drawing on analysis in Brookes (2020), which also draws on a study by Mendez et al (2011) and surveys of maize growers in 2015 and 2017 by Celeres:

- The average amount of insecticide active use and associated field EIQ/ha rating for GM IR maize in 2020 was 0.07 kg/ha and 1.9/ha respectively. This compared with conventional maize with herbicide active ingredient use of 0.287 kg/ha and a field EIQ rating of 9.25/ha;
- In 2020, the use of GM IR technology resulted a reduction in the use of insecticide active ingredient of 11,860 kg (-74%) and a reduction in the EIQ rating of 79%;

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[84] Based on AMIS Global data for the 2006-2009 period

- Cumulatively (2009-2020), the insecticide active ingredient usage saving has been 60% (277,000 kg), with an EIQ load reduction of 61%.

h) Vietnam

GM IR maize was first used in 2015, and in 2020 was planted on 9.2% of the total maize crop (92,000 ha of GM IR maize – all as stacked seed with both GM HT and GM IR traits).

Based on Kleffmann and Kynetec data and analysis by the author in 2017 and 2020, this shows that:

- The average amount of insecticide active ingredient and associated field EIQ/ha rating saved from no longer using insecticides targeted at the Asian Corn Borer pest was equal to 0.29 kg/ha, based on average insecticide use on the GM IR crop of 0.068 kg ai/ha and 0.356 kg ai/ha for conventional maize. The EI saving was 11.22/ha based on 2.86/ha for the GM IR maize crop and 14.06/ha for conventional maize (based on recorded insecticide use 2012-2014: sources: Kleffmann and Kynetec and Brookes and Dinh 2020). The maximum area on which these insecticides are annually applied is estimated to be about 725,000 ha;
- Based on these savings, over the six years of adoption of GM IR maize technology, the insecticide active ingredient usage saving and EIQ load reduction have respectively been 5.9% (a saving of 90,970 kg of insecticide active ingredient usage) and 5.8%.

i) Other countries

GM IR maize has also been grown on significant areas in the Philippines (since 2003: 683,300 ha planted in 2020), in Uruguay (since 2004: 117,690 ha in 2020), in Honduras (since 2003: 38,000 ha in 2020) and in Paraguay (since 2013, 518,400 ha in 2020). Due to limited availability on insecticide use on maize crops[85], it has not been possible to analyse the impact of reduced insecticide use and the associated environmental impact in these countries.

j) 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 61):

- In 2020, a 53.1% decrease in the total volume of insecticide ai applied (5.6 million kg) and a 60.7% reduction in the environmental impact (measured in terms of the field EIQ/ha load[86]);
- Since 1996, 41.2% less insecticide ai has been used (85.4 million kg) and the environmental impact from insecticides applied to the maize crop has fallen by 45.4%.

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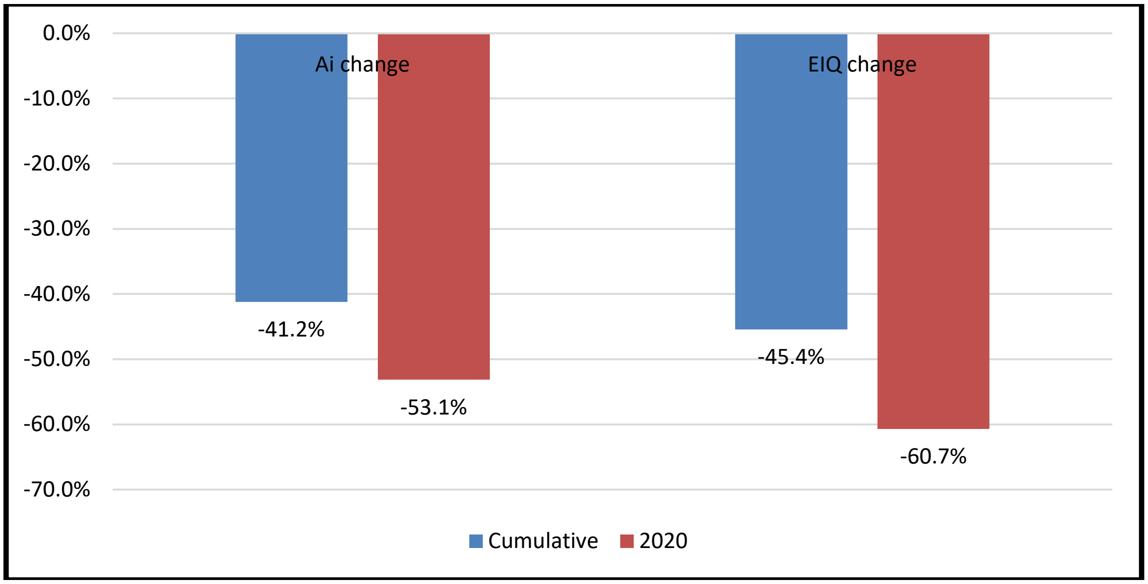
[85] Coupled with the 'non' application of insecticide measures to control some pests by farmers in many countries and/or use of alternatives such as biological and cultural control measures

[86] 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 61: Reduction in insecticide use and the environmental load from using GM IR maize in adopting countries 1996-2020



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 since the mid-1990s (Figure 62). 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));

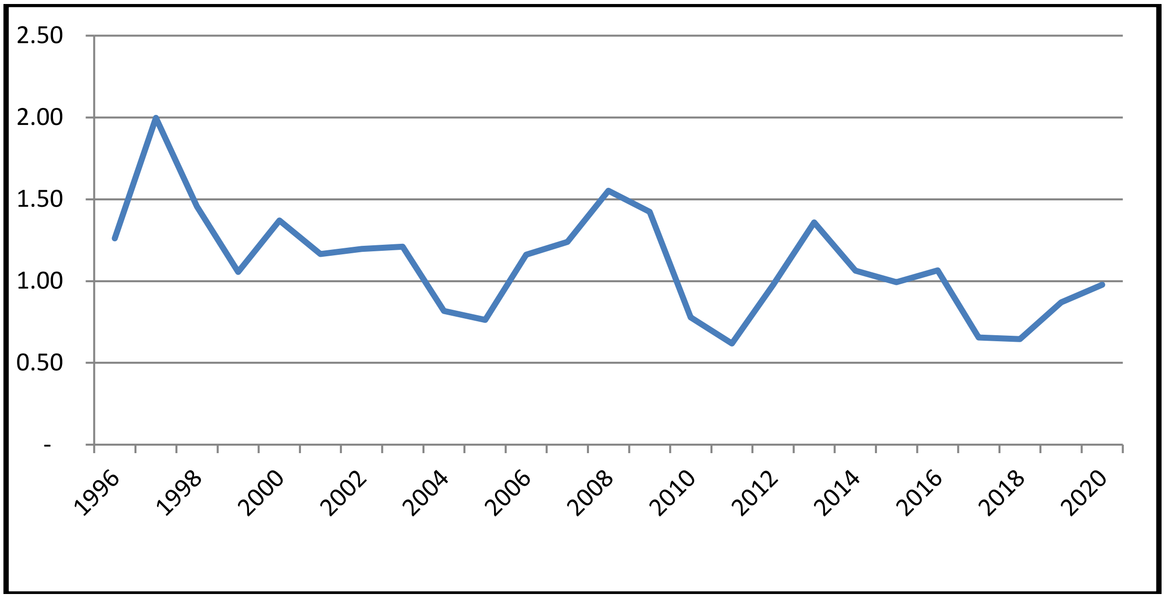
- Typically, the first users of the GM IR technology are farmers who regularly experience economic levels of damage from the GM IR target pests. This means that once the levels of adoption (in terms of areas planted to the GM IR traits) become significant (above 50% of the US crop from 2005, and 88% in 2020), 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 relevant literature (eg, Carpenter & Gianessi (1999), Sankala & Blumenthal (2003 & 2006)) and insecticide usage sources such as USDA NASS and Kynetec. 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. We identified that the average amount of insecticide active ingredient used for targeting these pests was about 0.14 kg ai/ha and the associated average EIQ/ha was about 6/ha.

As almost all of the US cotton crop has commonly received treatments each season for the control of these pests, these active ingredient and field EIQ saving 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 12% in 2020 (0.424 million kg) and the annual field EIQ load on the US cotton crop also fell by 16% in 2020. Since 1996, the cumulative decrease in insecticide ai use has been 8% (8.93 million kg), and the cumulative reduction in the field EIQ load has been 10%.

Figure 62: Average cotton insecticide usage: 1996-2020 (average active ingredient use: kg/ha)



Sources: derived from USDA NASS, University Extension Services and Kynetec

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)[87]. 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 from sources such as industry advisors and market research sources like Kleffmann and Kynetec put, for example, the current comparison as the average conventional treatment at 2.737 kg/ha, with a field EIQ/ha of 103.4/ha, compared to 1.67 kg/ha and a field EIQ/ha of 73.0/ha for GM IR cotton (see Appendix 3 for details).

Based on these differences, the amount of insecticide ai used and its environmental load impact were respectively 41% and 28% lower in 2020 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 30.1% (138.8 million kg ai) and the field EIQ load has fallen by 30.2%.

c) Australia

Using a combination of data from AMIS Global/Kleffmann, industry sources and CSIRO[88], 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 23);

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

[88] 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

- 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 has been respectively 53% (0.43 million kg) and 57% lower in 2020 than the levels that would have occurred if only conventional cotton had been planted;
- Cumulatively, since 1996 the volume of insecticide use is 30% lower (14 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 32%.

Table 23: 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)

d) Argentina

Adoption of GM IR cotton in Argentina has also resulted in important reductions in insecticide use[89]:

- 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 2020;
- 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 have been respectively 43% (143,940 kg) and 59% lower in 2020 than the levels that would have occurred if only conventional cotton had been planted;
- Cumulatively since 1998, the volume of insecticide use is 21.9% lower (1.82 million kg) and the EIQ/ha load 31.1% lower than the amount that would have been used if GM IR technology had not been adopted.

e) India

The analysis presented below is based on insecticide usage data from AMIS Global/Kleffmann and typical spray regimes for GM IR and conventional cotton (source: Monsanto India 2006, 2009, 2011, 2013 and 2017). The respective differences for ai use (see appendix 3) and field EIQ values for GM IR and conventional cotton used in 2020 are:

- Conventional cotton: average volume of insecticide used was 1.72 kg/ha and a field EIQ/ha value of 73.76/ha;
- GM IR cotton: average volume of insecticide used was 0.605 kg/ha and a field EIQ/ha value of 16.61/ha.

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[89] Based on data from Qaim and De Janvry (2005)

Based on these values, the level of insecticide ai use and the total EIQ load in 2020 were respectively 61% (13.7 million kg) and 72.8% lower than would have been expected if the total crop had been conventional cotton. Cumulatively, since 2002, the insecticide ai use was 36.4% lower (165 million kg) and the total EIQ load 46.2% lower.

f) Brazil

GM IR cotton was first planted commercially in 2006 (in 2020, on 1.17 million ha, 77% 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 2020 were respectively 34% (382,000 kg) and 46% lower than would have been expected if the total crop had been conventional cotton. Cumulatively since 2006, the total active ingredient saving has been 2.5 million kg (18%) and the EIQ/ha load factor has fallen by 26%.

g) Mexico

GM IR cotton has been grown in Mexico since 1996, and in 2020, 103,300 ha (69% 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 2020, at a national level, there had been a 21.4% saving in the amount of insecticide active ingredient use (168,000 kg) applied relative to usage if the whole crop had been planted to conventional varieties. The field EIQ load was 21.2% lower;
- Cumulatively since 1996, the amount of insecticide active ingredient applied was 16.6% (3.2 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 16.5% lower than it would otherwise have been if the whole crop had been using conventional varieties.

h) Colombia

GM IR cotton has been grown commercially in Colombia since 2002. In 2020, 54% of the cotton crop (4,615 ha of GM HT cotton) used seed containing this trait.

Drawing on analysis in Brookes (2020), which also draws on surveys of cotton growers in 2015 and 2017 by Celeres:

- The average amount of insecticide active use and associated field EIQ/ha rating for GM IR cotton in 2020 were 0.3 kg/ha and 8.49/ha respectively. This compared with conventional cotton with insecticide active ingredient use of 0.69 kg/ha and a field EIQ rating of 20.29/ha;
- In 2020, the use of GM HT technology resulted a reduction in the use of insecticide active ingredient of 1,560 kg (-26%) and a reduction in the EIQ rating of 31%;
- Cumulatively (2002-2020), the insecticide active ingredient usage saving has been 59% (182,120 kg), with an EIQ load reduction of 63%.

i) Other countries

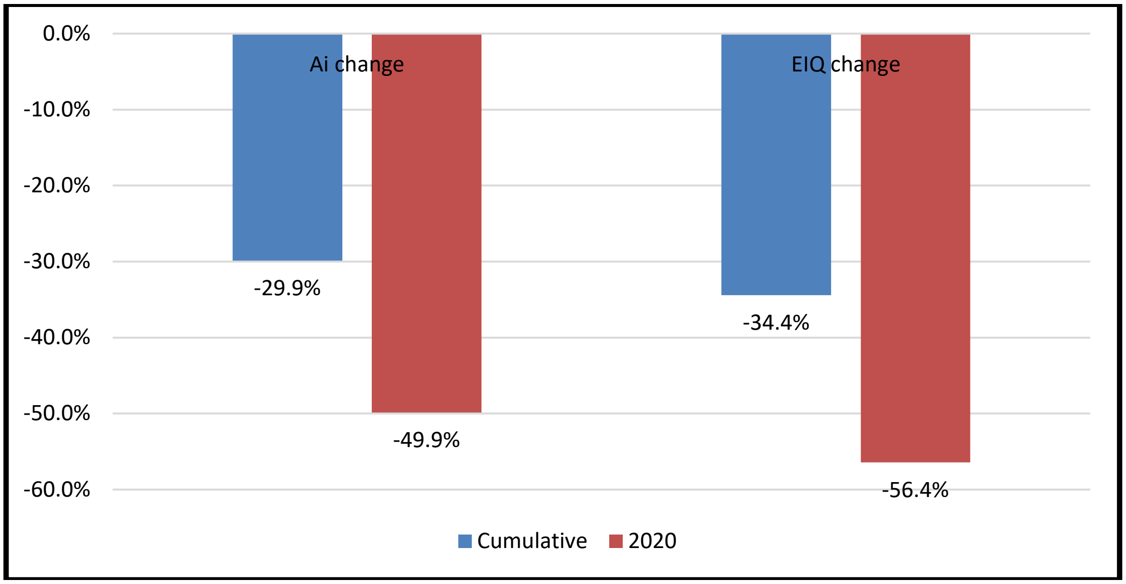
Cotton farmers in South Africa, Burkina Faso, Pakistan, Myanmar and Sudan have also been using GM IR technology in recent years. Analysis of the impact on insecticide use and the associated environmental 'foot print' are not presented for these crops because of the lack of insecticide usage data.

j) 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 63):

- In 2020, a 49.9% decrease in the total volume of insecticide ai applied (18.8 million kg) and a 56.4% reduction in the environmental impact (measured in terms of the field EIQ/ha load);
- Since 1996, 29.9% less insecticide ai has been used (338.9 million kg) and the environmental impact from insecticides applied to the cotton crop has fallen by 34.4%.

Figure 63: Reduction in insecticide use and the environmental load from using GM IR cotton in adopting countries 1996-2020



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, 169 weed species that are resistant to ALS herbicides (eg, imazethapyr, cloransulam methyl) and 87 weed species resistant to photosystem II inhibitor herbicides (eg, atrazine). Worldwide there are currently (accessed May 2022) 56 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 17,11 and 8. Some of the glyphosate-resistant species, such as marestail (*Conyza canadensis*), waterhemp (*Amaranthus tuberculatus*) and palmer pigweed (*Amaranthus palmeri*) in the US, are now widespread, with the affected area being possibly within a range of 60%-80% 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 advised to be proactive and include other herbicides (with different and complementary modes of action) in combination with glyphosate and in some cases to adopt cultural practices such as ploughing in their 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 technology solutions for their control. In addition, as referred to earlier, GM HT crops tolerant to other herbicides (often stacked with glyphosate) have also become available from 2016 in some countries (notably to dicamba and 2 4 D in the USA). At the macro level, these changes have influenced the mix, total amount, cost and overall profile of herbicides applied to GM HT crops in the last 20 years.

For example, in the 2020 US GM HT soybean crop, approximately 90% of the crop area was planted to varieties that were tolerant to other herbicides (in addition to tolerance to glyphosate) and even where crops were planted that were tolerant to only one herbicide, all of these crops received an additional herbicide treatment of other active ingredients (notably sulfentrazone, S metolachlor, 2 4 D, metribuzin, metsulfuron and pyroxasulfone). This compares with only 14% of the GM HT soybean crop (almost all tolerant to only glyphosate) receiving a treatment of one of the next four most used 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) doubled over this period. The increase in non-glyphosate herbicide use was 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 by 2016, glyphosate accounted for a lower share of total active ingredient use on the GM HT crop (63%) than in 1998 when it accounted for 82% of total active ingredient use. This illustrates that farmers have continued to use glyphosate because of its broad-spectrum activity in addition to using other herbicides in line with integrated weed management advice. This continues in 2020, with the availability of additional options for weed control via varieties with GM HT tolerance to other herbicides. Almost all of the new GM HT seed technology used is tolerant to glyphosate and other herbicides rather than being only tolerant to other (than glyphosate) herbicides.

On the small conventional (soybean) crop, the average amount of herbicide active ingredient applied also doubled over the period 2006-2020. This increase in usage largely reflected 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 mainly 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.

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 Soil 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 (CO_2), nitrous oxide (N_2O) and methane (CH_4). 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' and 'reduced-till' 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 soil preparation; ploughing, harrowing, rolling etc);
   - Reduced labour requirements associated with soil preparation;
   - Enhanced soil quality and reduced levels of soil erosion, resulting in more carbon remaining in soil, which leads to lower GHG emissions[90];
   - 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)); and

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[90] The International Panel on Climate Change (IPCC) has agreed that conservation/no till cultivation leads to higher levels of soil carbon. https://www.ipcc.ch/2019/08/08/land-is-a-critical-resource_srccl/

c) Additional carbon dioxide can be assimilated where the GM technology leads to the intensification of crop production resulting in higher crop yields, additional cropping and the use of cover crops (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 and sequestration of carbon in the soil with NT/RT 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): conventionally tilled prior to planting the next crop (residue cover 0%-15%) eg, inversion tillage using a plough followed by multiple cultivation trips;
- Reduced tillage (RT): full width tillage that disturbs the entire soil surface prior to planting the next crop, tillage tools such as chisel ploughs, field cultivators, rotary harrows are used and weeds are controlled by cultivation and herbicides. With RT methods of mulch-till and ridge till, crop residue remains on the surface (this corresponds to a residue cover of 16%-30% for all crops other than maize, for which there is a reduced tillage category with a higher crop residue cover of 31%-50%); and
- 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. NT methods include zero-till, slot till, direct seeding and strip-till. The soil is not tilled prior to planting the next crop and substantial crop residue remains on the surface (this corresponds to a residue cover of >30% for all crops other than maize, for which the residue cover is >50%).

4.2.1 Tractor fuel use

a) Reduced and no tillage

The adoption and (more importantly) maintenance of conservation tillage systems, notably NT systems, has been facilitated by the availability of GM HT crops. To estimate fuel savings from conservation tillage systems, 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) Conservation Effects Assessment Project (CEAP); the USDA Energy Estimator for Tillage Model (2014); and the USDA online tool for estimating carbon storage in agroforestry practices (COMET-VR):

- The USDA's Conservation Effects Assessment Project (CEAP) uses the Soil Intensity Rating (STIR) to calculate the rate of soil disturbance for each form of tillage method, their frequency and depth. For each implement used, fuel consumption was estimated and given a diesel equivalent for each tillage implement used. For example, a no-till drill has a STIR of 2 and consumes 3.3 litres/ha, a chisel plough has a STIR of 78 and consumes 10.3 litres/ha, a mouldboard plough a STIR of 87 and consumes 17.6 litres/ha. For land to be considered under NT cultivation, the STIR value for each crop in the rotation should be no great than 20, for RT (mulch-till) the STIR value should be greater than 60. The relative differences in the quantity of fuel used for each tillage type is illustrated in the Table 24 below;

Table 24: Estimated reduction in fuel use from adoption of conservation tillage (litres/ha)

Tillage type	STIR	Fuel use	*Saving on CT*
CT	>60	56.6	
NT	<20	17.7	-38.9
RT (mulch till)	>20 - <60	33.3	-23.3

Source: USDA CEAP-Crop Conservation Insight August 2016

The USDA CEAP-Crop Conservation Insight (2016) estimated that annually in the US the widespread adoption of conservation tillage has resulted in:

- ➢ Fuel use reduction of 3,075.3 million litres of diesel equivalents, roughly equal to the energy used by 3.2 million US households;
- ➢ Carbon dioxide emissions reduced by 8.3 million tonnes; and
- ➢ NT has been adopted on 53% of **all** cropping land and accounts for 72% of the reduction on fuel use and related emissions.

- 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 US and compares potential energy savings between conventional tillage 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 25). CT requires 49.01 litres/ha, compared to mulch till at 40.88 litres/ha, ridge till 32.36 litres/ha and NT 21.79 litres/ha;

Table 25: US soybean: tractor fuel consumption by tillage method (litres/ha)

Year 1 – Illinois	**CT**	**Mulch till**	**Ridge-till**	**NT**
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**
Saving on CT:		***8.13***	***16.65***	***27.22***

Source: USDA Energy Estimator 2012

- The fuel saving obtained by a switch from CT to mulch-till, ridge-till and NT for maize and soybeans across the three most important crop management zones (CMZ's) in the US is illustrated in Table 26. The adoption of NT in maize results in a 24.41 litre/ha saving compared with CT and in the case of soybeans, the NT saving is 27.12 litre/ha[91], a saving of 44.8% and 55.3% respectively; and

Table 26: Total farm diesel fuel consumption estimate (litres/ha)

Crop (crop management zones)	**CT**	**Mulch-till**	**Ridge-till**	**NT**
Maize (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 CT:		***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 on CT:		***21.2%***	***31.2%***	***55.3%***

Source: USDA Energy Estimator 2012

- The Voluntary Reporting of Greenhouse Gases-Carbon Management Evaluation Tool (COMET-VR) gives a higher reduction of 41.8 litres/ha when CT is replaced by NT on non-irrigated maize and a reduction of 59.7 litres/ha in the case of soybeans in Nebraska.

In our analysis[92] 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 CT 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 CT. These are conservative estimates and are in line with the USDA Fuel Estimator for soybeans and maize.

In terms of GHG, each litre of tractor diesel consumed contributes an estimated 2.67[93] 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/ha and 27.74 kg/ha respectively for soybeans and 65.17 kg/ha and 20.08 kg/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 application is with a 90-foot boom sprayer which consumes approximately 0.84 litres/ha[94] (0.65

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

[92] 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 for both maize and soybeans.

[93] In previous editions of this report up to 2010 the authors have applied a co-efficient of 2.75 to convert 1 litre of diesel to kgs of carbon dioxide. All subsequent reports use the updated figure of 2.6676 rounded to 2.67.

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

litres/ha for a self-propelled sprayer and 1.12 litres/ha for a tractor pulled sprayer (Lazarus (2019)). One less spray application therefore reduces carbon dioxide emissions by 2.24 kg/ha.

The conversion of one hectare of CT to NT equates to a saving of approximately 587 km travelled by a standard family car[95] and one less spray pass per hectare is equal to a saving of nearly 18.2 km travelled.

4.2.2 Soil carbon sequestration

The use of RT/NT farming systems increases the amount of organic soil carbon in the upper soil layer in the form of crop roots and harvest residue that is not otherwise inverted into the sub-soil if CT is used. 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.

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 CT to NT and RT based on a meta-analysis of the relevant literature (Table 27). In this tool, coefficients are generalized at the national-scale and differentiated by dry and humid climate zones with the values shown as 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[96].

Table 27: COMET-Planner: carbon sequestration by conservation practice (average)

Conservation Practice Standard	Climate zone	Carbon dioxide (kg CO_2 eq/ha/year)	Carbon (kg carbon/ha/year)
CT to NT (CPS 329)	Dry/semi arid	568.3	154.9
	Moist/humid	1,037.8	282.8
CT to RT (CPS 345)	Dry/semi arid	247.1	67.3
	Moist/humid	321.2	87.5

Source: COMET-Planner Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning
Notes: 1 kg carbon equals 3.67 kg carbon dioxide

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[95] Assumed standard UK family car carbon dioxide emission rating = 123.4 grams/km. Therefore 72.41 kg of carbon dioxide divided by 123.4 grams/km = 587 km.

[96] Personal communication November 2019: E.D.Mass, Ohio State University Carbon Management and Sequestration Center has observed similar carbon sequestrations rates of approximately 282.8 kg/C/ha/yr in the initial twenty years of conversion from CT to NT with an anticipated average of 178 kg/C/ha/yr over fifty years

Our analysis for the US uses the COMET-VR 2.0 tool[97] for three key soybean and maize production states and assumes the adoption of NT from CT in all states, a clay loam soil with average fertiliser usage, a non-irrigated maize-soybean rotation in Minnesota and Illinois and a soybean-maize-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 Calculator[98] for maize-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 maize 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 maize NT and CT is 247 kg carbon/ha/year and for soybeans 103 kg carbon/ha/year (Table 28).

Table 28: Summary of the potential of maize and soybeans cultivation systems to reduce net emissions or sequester carbon (kg of carbon/ha/year)

		Carbon sequestered	***Carbon sequestered - difference to NT***
Maize	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

Differences in carbon soil sequestration rates between maize and soybeans can be partially explained by the greater plant matter residue contribution of the maize crop in the soybean-maize rotation. Research by Alvarez & Steinbach (2012) estimated that maize contributes 7,178 Mg/ha/year of dry matter as crop residue compared to soybeans which contribute only 3,373 Mg/ha/year. Soybean roots have less mass and length than maize roots which may also influence different rates of soil carbon sequestration.

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[97] 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 N_2O emissions and CO_2 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/

[98] http://surf.kbs.msu.edu/

Overall, the literature highlights the difficulty in estimating the contribution NT/RT systems to soil carbon sequestration levels. If a specific crop area is in continuous NT crop rotation, the full soil carbon sequestration (storage) 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 reliant on having an effective (typically herbicide-based) weed control system. As discussed later, the increasing emergence of weeds resistant to glyphosate (the main herbicide used for 'over the crop' weed control in GM HT crops) has reduced the effectiveness of weed control systems solely based on herbicide use for some farmers and resulted in some reversion to CT production systems in order to improve their overall levels of weed control. This has likely reduced the year on year absolute levels of carbon sequestration facilitated by GM HT crops relative to several years ago (see for example Lu et al (2022), Van Deynze et al (2021)). The estimates presented in this paper take this factor of influence into account by using the latest available data on the adoption of NT, RT and CT production systems.

Estimating long-term soil carbon sequestration is also complicated by the hypothesis typically used in soil carbon models that the level of soil organic carbon (SOC) reaches an equilibrium when the amount of carbon stored in the soil equals the amount of carbon released (the Carbon-Stock Equilibrium (CSE)). This implies that as equilibrium is reached, the rate of soil carbon sequestration may decline and therefore if equilibrium is being reached after many years of land being in NT with GM HT crops, the rate of carbon sequestration may be declining. The estimates presented in this paper assume that a constant rate of carbon sequestration occurs because of the relatively short time period that NT/RT production systems have been operated (the time period that land may have been in 'permanent non-cultivation is a maximum of 20-25 years). In addition, some researchers question whether the CSE assumption that is used in most soil models is valid because of the scope for very old soils to continue to store carbon (Lal, 2004).

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 (covering the period up to 1996-2011) no differentiation was made between maize 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 release 25 kg of carbon/ha/year).

In this report (and the previous five), the soil carbon sequestered by tillage system for <u>maize</u> 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 <u>soybeans</u> in a continuous rotation with maize is assumed to be a net reduction of 100 kg of carbon/ha/year (all soybean tillage systems emit carbon but the NT and RT systems emit less relative to the CT system) 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 GM crop seed technology has resulted in a reduction in the number of herbicide or insecticide applications 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* (2005)). 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 CT to RT and NT. This has had a marked effect on tractor fuel consumption due to energy-intensive cultivation methods being replaced with RT/NT and largely herbicide-based weed control systems. The GM HT crop where this is most evident is HT soybeans. Here, adoption of the technology has made an important contribution to facilitating the adoption of RT or NT farming systems. Before the introduction of GM HT soybean cultivars, RT/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 RT/NT systems more reliable, technically viable and commercially attractive. These technical and cost advantages have contributed to the rapid adoption of GM HT seed and RT/NT production systems. For example, there has been a 45% increase in the RT/NT soybean area in the US and a six-fold increase in Argentina since 1996. In 2020, RT/NT production accounted for 80% and 92% respectively of total soybean production in the US and Argentina, with 84% and 94% respectively of the RT/NT soybean crop area in each countries using GM HT technology.

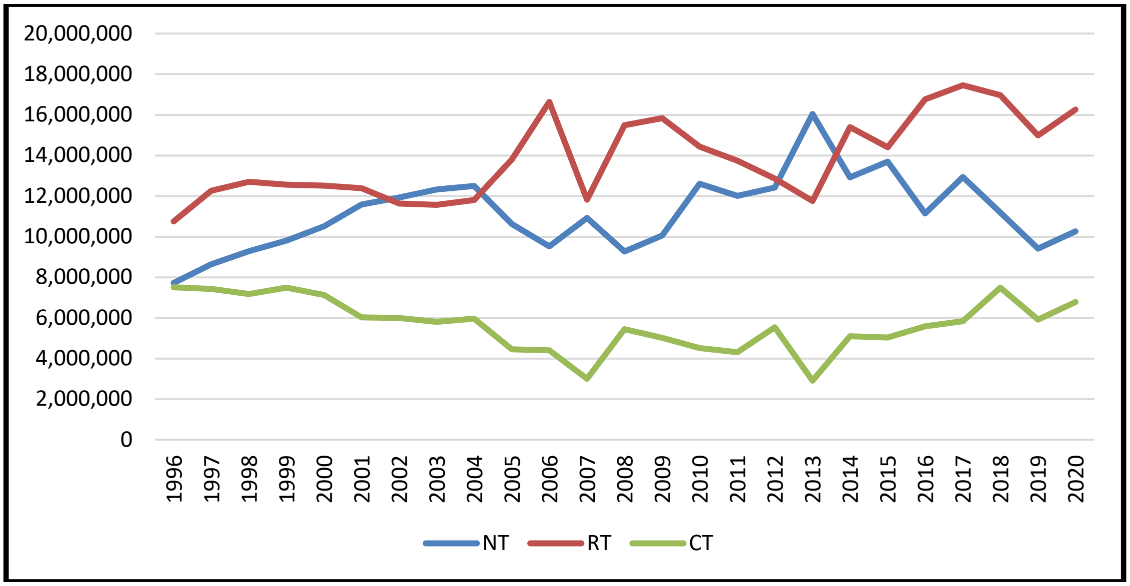
4.2.4 Herbicide tolerant soybeans

4.2.4.1 The US

The importance of GM HT soybeans in the adoption of a NT system was first highlighted by a detailed study undertaken by the American Soybean Association "The Conservation Tillage Study[99]" (2001). 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. Fernandez-Cornejo *et al* (2012) concluded over an eleven-year period (1996-2006) that GM HT soybean adoption had led to a significant increase in the adoption of conservation tillage (RT/NT). This study concluded that a one percent increase in GM HT soybean adoption leads to a 0.21% increase in conservation tillage.

The area of soybeans cultivated in the US has increased substantially (28%) from 26.0 million ha in 1996 to 33.3 million ha in 2020. Over the same period, the soybean area planted using NT and RT has changed significantly. The CT area fell from 7.51 million ha in 1996 to 2.9 million ha in 2013 before increasing to between 5 and 7 million ha in recent years (6.8 million ha in 2020). The area planted using RT[100] increased from 10.8 million ha in 1996 to a high of 17.5 million ha in 2017 (16.3 million ha in 2020) and the area planted using NT increased from 7.7 million ha in 1996 to a high of 16.0 million ha in 2013 before falling back to 10.3 million ha in 2020 (Figure 64). Barrera (2016) identified a reduction in the area of NT in 2015, while RT saw a nominal increase for both maize and soybeans and the changes presented here confirm this recent trend as more farmers revert to CT production systems in order to improve control of weeds exhibiting resistance to glyphosate (and other herbicides).

Figure 64: US soybean: crop area by tillage practices 1996-2020 (hectares)



Adapted from Conservation Technology Information Center's (CTIC) National Crop Residue Management farm survey - https://www.ctic.org/CRM 1996-2004 & Operational Tillage Management System -

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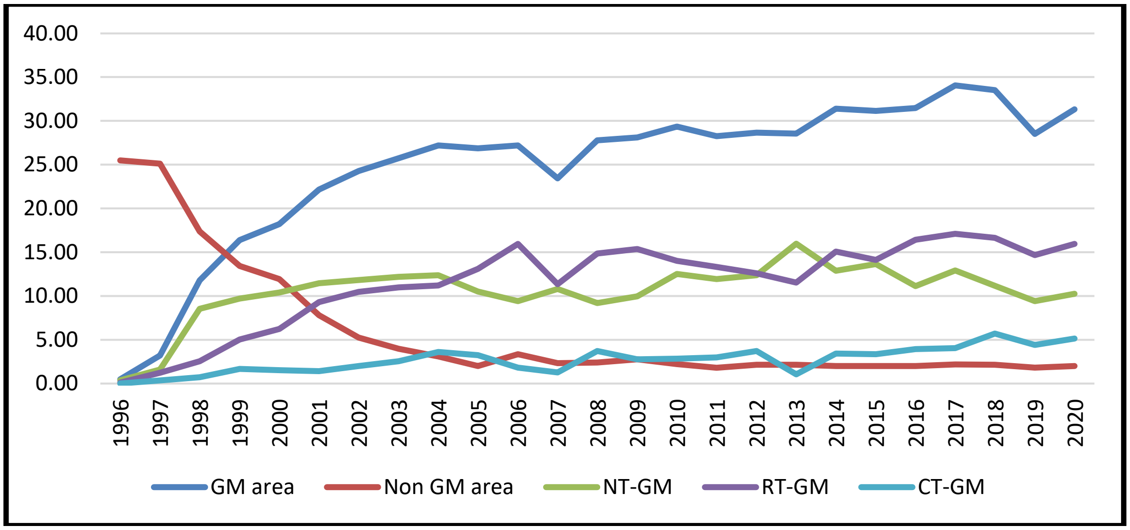
[99] https://soygrowers.com/news-releases/asa-study-confirms-environmental-benefits-of-biotech-soybeans/

[100] Includes some pre-planting minimum tillage with 16-30% crop residue

https://www.ctic.org/OpTIS ased on remote sensing data for top five cropping states - Illinois, Iowa, Nebraska, Indiana & Minnesota 2005-2020.

The most rapid rate of adoption of the GM HT technology has been by farmers using NT/RT systems (GM HT cultivars accounting for an estimated 95% of total NT soybeans by 2006 and 95% in RT soybeans by 2014). This compares with CT systems where GM HT cultivars account for an estimated 76% of total CT plantings in 2020 (Figure 65).

Figure 65: US GM HT soybeans by tillage 1996-2020 (million ha)

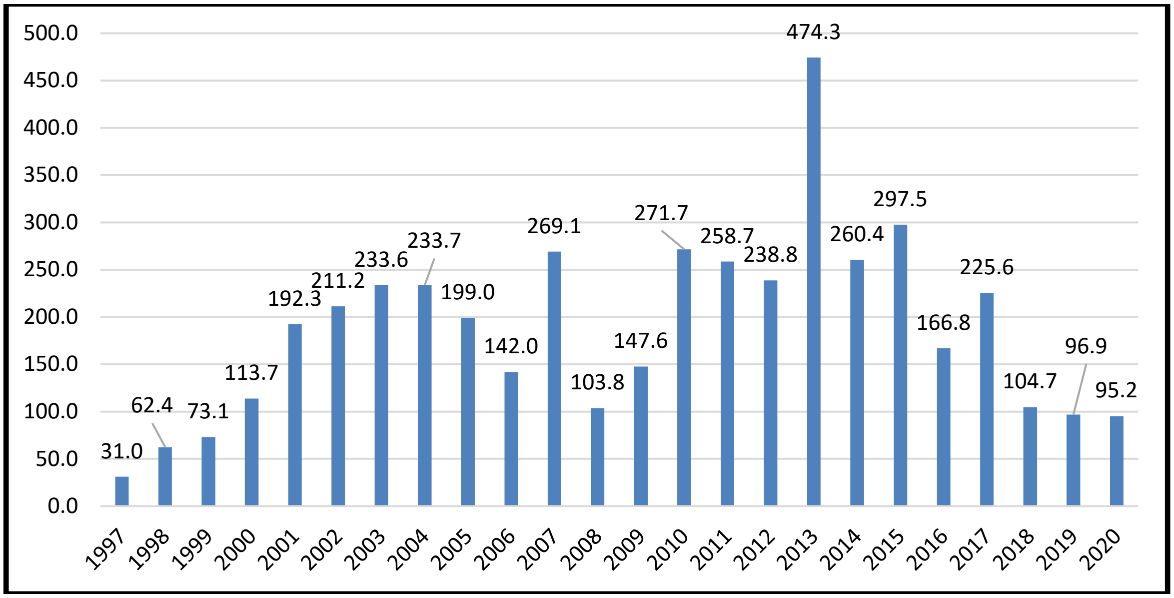


a) Fuel consumption

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 24% (233 million litres) between 1996 and 2020 while the area planted increased by 28%. Over the same period, the average fuel usage fell 2.8% (from 36.6 litres/ha to 35.6 litres/ha). In 2020, the average tillage fuel consumption on the GM HT planted area was 34.8 litres/ha compared to 47.0 litres/ha for the conventional non-GM crop.

These changes to tillage fuel use and the resultant reduction on carbon dioxide emissions in US soybeans for the 1996-2020 period are summarised in Figure 66. Cumulatively, this amounted to a permanent reduction in tillage fuel usage of 1,687 million litres which equates to a reduction in carbon dioxide emission of 4,503 million kg over this period.

Figure 66: US soybeans permanent reduction in carbon dioxide emissions resulting from a reduction in fuel use 1996-2020 (million kg)



b) Soil carbon sequestration

Using estimates of the soil carbon sequestered by tillage system for maize 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)[101] and based on the crop area planted by tillage system and type of seed planted (GM HT and conventional non-GM), our estimates of soil carbon changes are summarised below:

- The average level of carbon released per ha decreased by 3.4% (3.5 kg carbon/ha/year) from 102.9 to 99.5 kg carbon/ha/year. In 2013 when the area in NT was at its highest the average release dropped to 81.3 kg/carbon/ha/yr;
- Although the area planted to soybeans in 2020 was 28% higher (at 33.3 million ha) than in 1996, the rate of total carbon released into the environment increased by only 24.1% (a release of 2,672 million kg in 1996 compared to 3,316 million kg carbon/year in 2020).

Cumulatively, since 1996 the increase in soil carbon sequestered due to the increase in RT and NT in US soybean production systems has been 5,978 million kg of carbon which, in terms of carbon dioxide emissions, equates to a saving of 21,938 million kg of carbon dioxide that would otherwise have been released into the atmosphere (Appendix 6). In 2013, the additional carbon sequestered peaked at 663 million kg (2,433 million kg carbon dioxide) when the average increase in carbon sequestered relative to 1996 was 21.6 kg carbon per ha (Figure 67). Readers should note that these estimates take into consideration the loss in carbon sequestration that has arisen as some of the land using RT/NT has returned to CT in order to address weed resistance issues.

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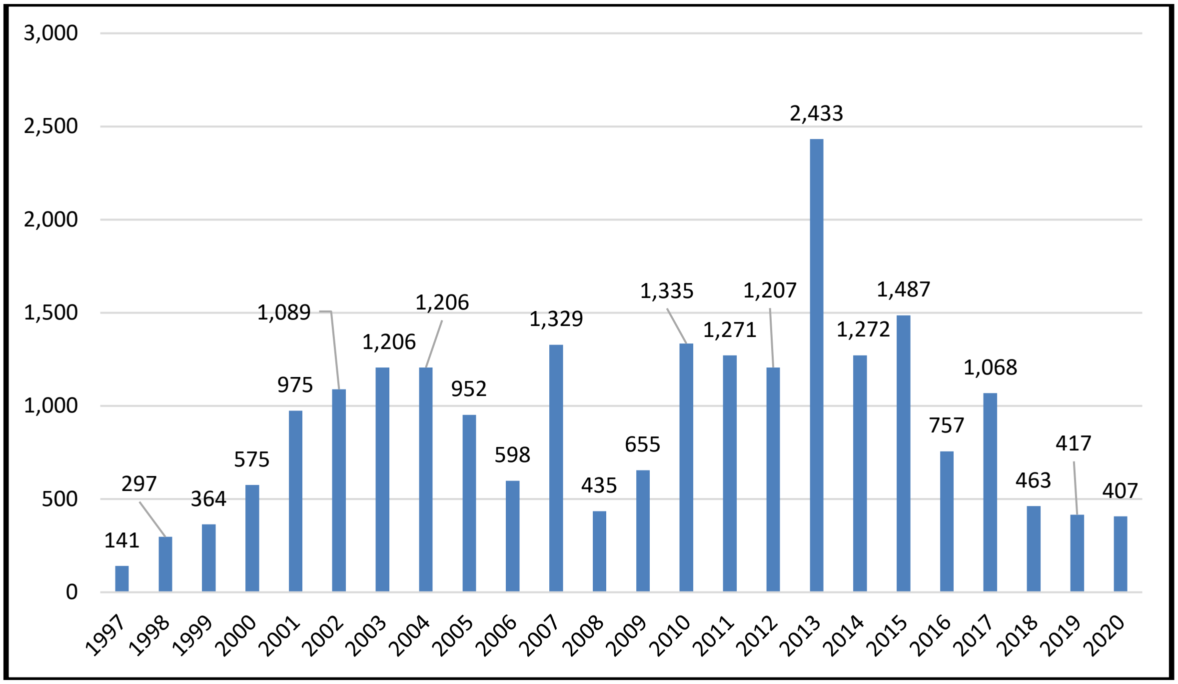
[101] The actual rate of soil carbon sequestered by tillage system is, however, dependent upon soil type, soil organic content, quantity and type of crop residue, so these estimates are indicative averages

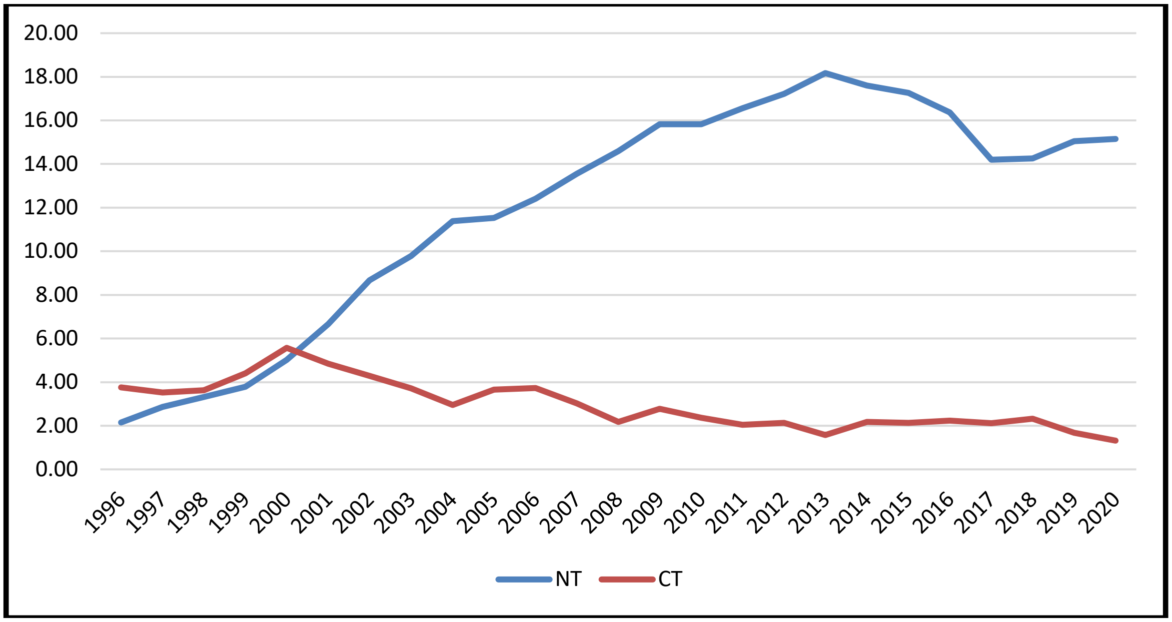
Figure 67: US soybeans - potential additional carbon dioxide sequestered 1996-2020 (million kg)



4.2.4.2 Argentina

Since 1996, the area planted to soybeans in Argentina, has increased substantially from 5.9 to 16.5 million ha (+180%). Over the same period, the area planted using NT practices also increased by seven fold from an estimated 2.2 to 15.1 million ha, whilst the area planted using CT decreased from 3.8 to 1.3 million ha (Figure 68).

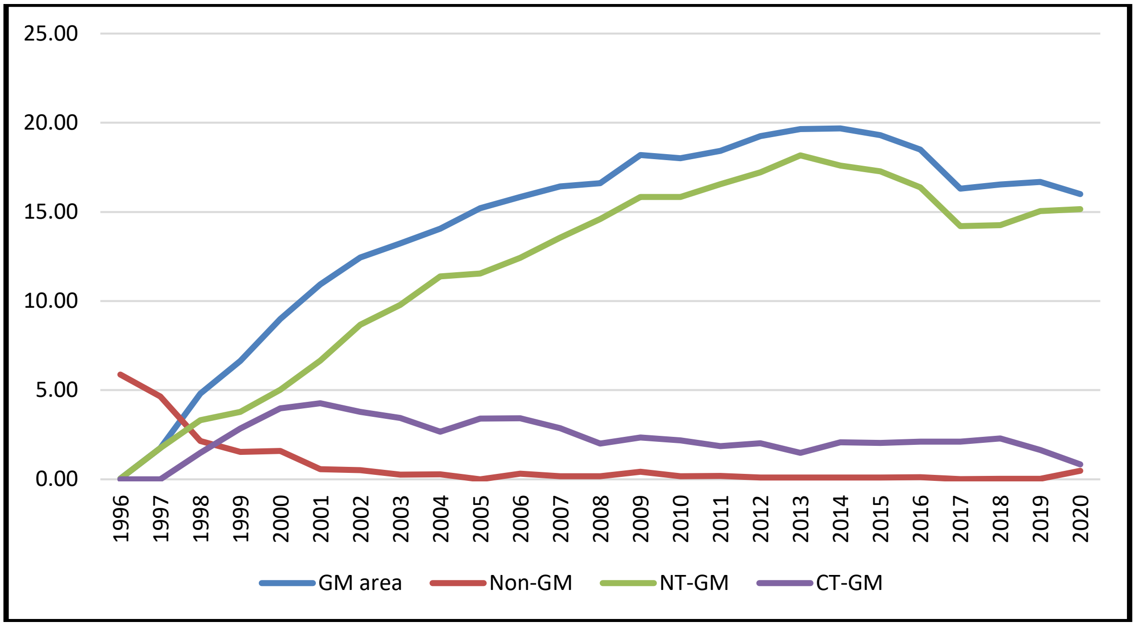
Figure 68: Argentina soybeans tillage practices 1996-2020 (million ha)



Adapted from Benbrook (2005), Trigo (2016) and AAPRESID (2018), Argenbio (2020)

As in the US, a key driver for the growth in NT soybean production has been the availability of GM HT soybeans (Figure 69), which in 2020, accounted for 97% 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-1990's, 5%-10% of the total soybean crop was a second crop following on from wheat (in the same season). In the last twenty 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).

Figure 69: Argentina GM HT soybeans by tillage practice 1996-2020 (million ha)



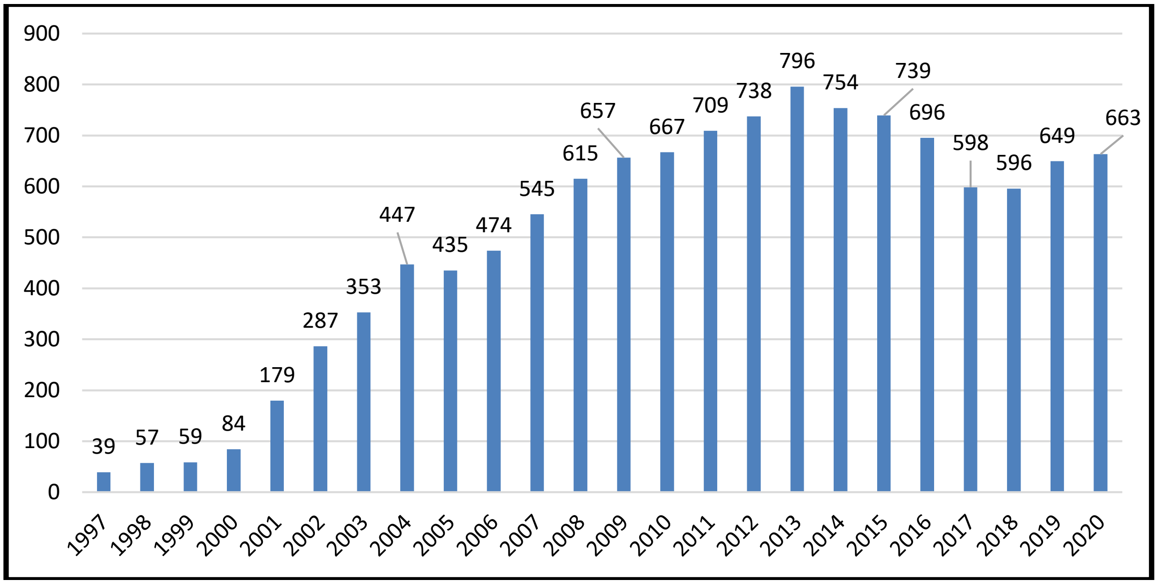
During the 1990's and early 2000's, NT stimulated an increase in the soybean-maize rotation which reduced insect pressure, restored soil organic matter (SOM), increased crop residue input and nutrient cycling. Therefore, the use of maize and other cover crops in the soybean rotation has resulted in a 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 1990's, NT farming helped to reduce soil erosion by over 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, higher crop yields, as well as, reducing fuel use and labour costs. However, AAPRESID also estimate that the area of NT in Argentina peaked in 2012 at 92% and fell back marginally subsequently (eg, to 90% in 2015) due to difficulties some farmers have faced with the control of glyphosate resistant weeds, necessitating reverting to ploughing to improve weed control and soil tyre compaction (Argentine No-Till Farmers Association (AAPRESID) (2018)). Interestingly, in 2020 their estimate of the proportion of the Argentine soybean crop using NT was higher at 92%.

a) Fuel consumption

Between 1996 and 2020, total fuel consumption associated with soybean cultivation increased by 71% from 231.5 to 396.2 million litres/year. However, during this period, the average quantity of fuel used per ha fell 39% from 39.1 to 24.1 litres/ha, due mainly to the widespread adoption of GM HT soybean seed and NT systems. If the proportion of the soybean crop in 2020 in NT production had remained at the NT share level applicable in 1996, an additional 4,433 million litres of fuel would have been used and at this level of fuel usage, an additional 11,837 million kg of carbon dioxide would otherwise have been released into the atmosphere (Figure 70).

Figure 70: Argentina soybeans permanent reduction in carbon dioxide emissions resulting from a reduction in fuel use 1996-2020 (million kg)



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-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 systems[102]) 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.

Specific research into soil carbon sequestration in Argentina includes the following:

- 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;

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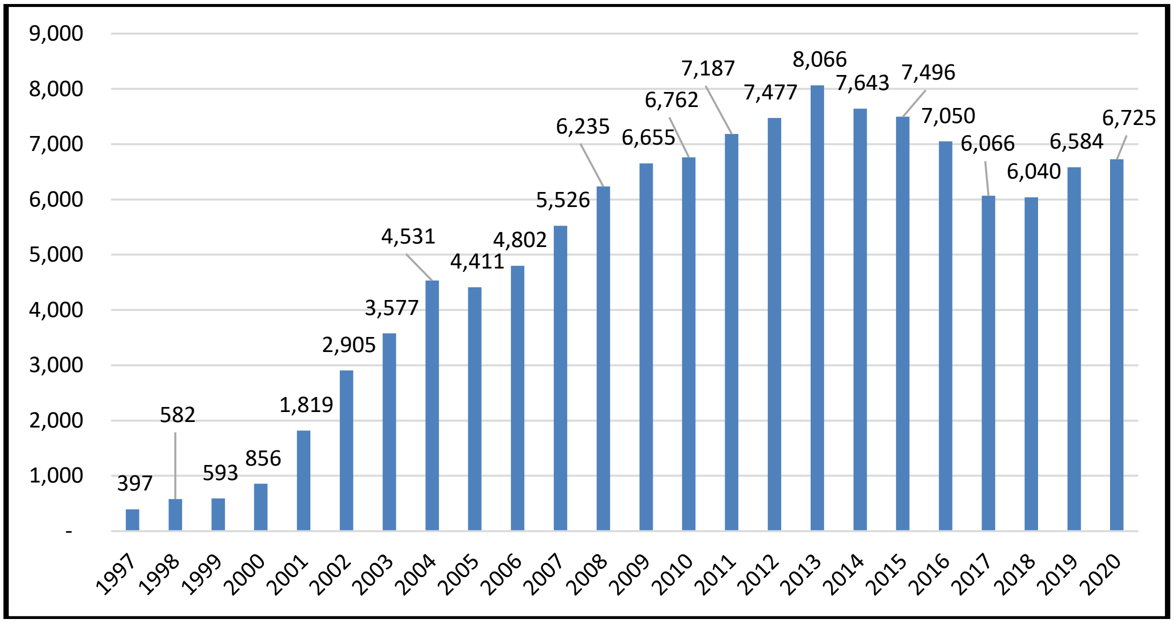
[102] Trials conducted by INTA found that direct sowing increases the yields of wheat and second soybean crop in rotation. Other benefits observed were: less soil inversion leaving a greater quantity of stubble on the surface, improvements in hydraulic conductivity, more efficient use of soil water,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

- Steinbach (2006) modelled the impact on the conversion of the Argentinean Pampas to NT 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 NT after 35 years;
- Derpsch *et al* (2010) estimated that two-thirds of the area under NT systems in South America was permanently in NT, which in Argentina was over 70% of the NT crop area. This suggested that these carbon sequestration gains may be of a permanent nature; and
- Results from a 15-year experiment in the semi-arid Argentine Pampa (Alvarez *et al* (2014)) to evaluate a combination of three tillage systems (NT, NT with cover crop in winter and RT) and two crop sequences (soybean–maize and soybean monoculture) concluded both factors (tillage system and crop sequence) affects the total organic carbon (TOC) stock. The total organic carbon stock, up to a depth of 100 cm showed significant differences between soils under different tillage systems, with the two NT systems having an 8% higher stock than the RT system (an extra accumulation of 333 kg TOC/ha/year). In addition, at 0–30 cm depth, the NT systems had 267 kg TOC/ha/year more than the RT system. The crop sequence of soybean–maize also had a 3% higher level of organic carbon up to 100 cm soil depth (an extra accumulation of 133 kg TOC/ha/year) than the soybean monoculture crop system.

Our analysis below applies a conservative estimate of soil carbon retention of 175 kg carbon/ha/yr for NT and a <u>release</u> of 25 kg carbon/ha/yr for CT soybean cropping in Argentina. This estimates that the widespread adoption of NT/RT production systems, facilitated by GM HT soybean technology has resulted in a cumulative total of 32,693 million kg of carbon, which equates to a saving of 119,985 million kg of carbon dioxide having been retained in the soil that would otherwise have been released into the atmosphere (Figure 71 and Appendix 6).

Figure 71: Argentina soybeans - potential additional carbon dioxide sequestered 1996-2020 (million kg)

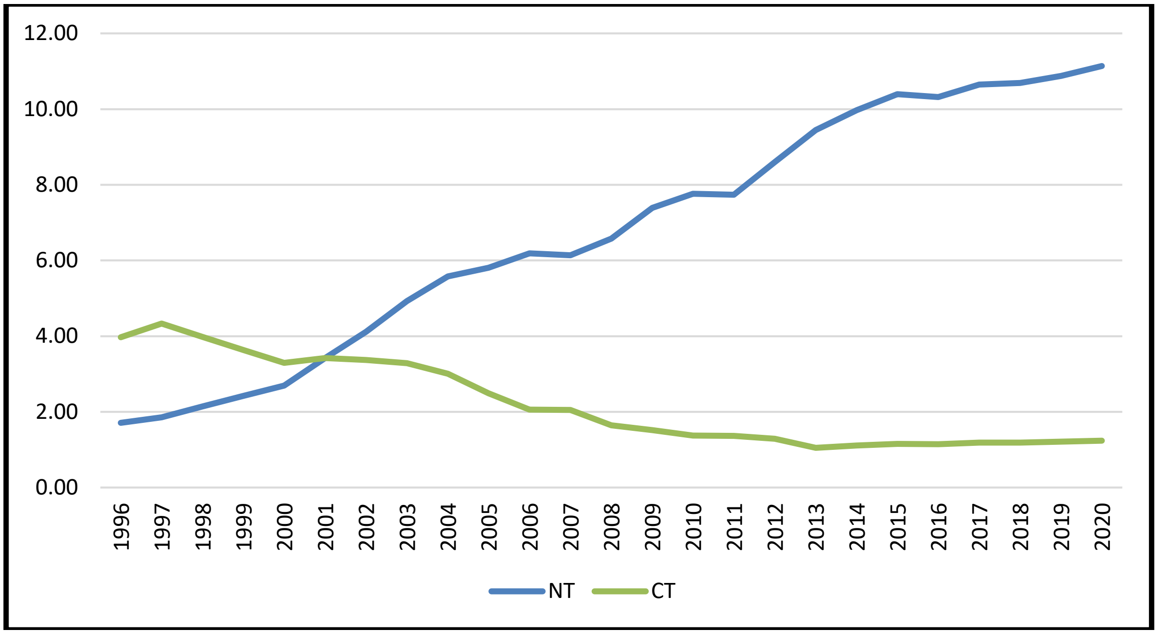


4.2.4.3 Brazil

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, 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 36.7 million ha in 2020, of which these southern states accounted for 32.4% (12.4 million ha). The vast majority of soybean production in these states uses NT systems (94%: 11.1 million ha), with virtually all of the NT area being GM HT soybeans (Figure 72).

Figure 72: Brazil soybeans tillage practices 1996-2020 (million ha)

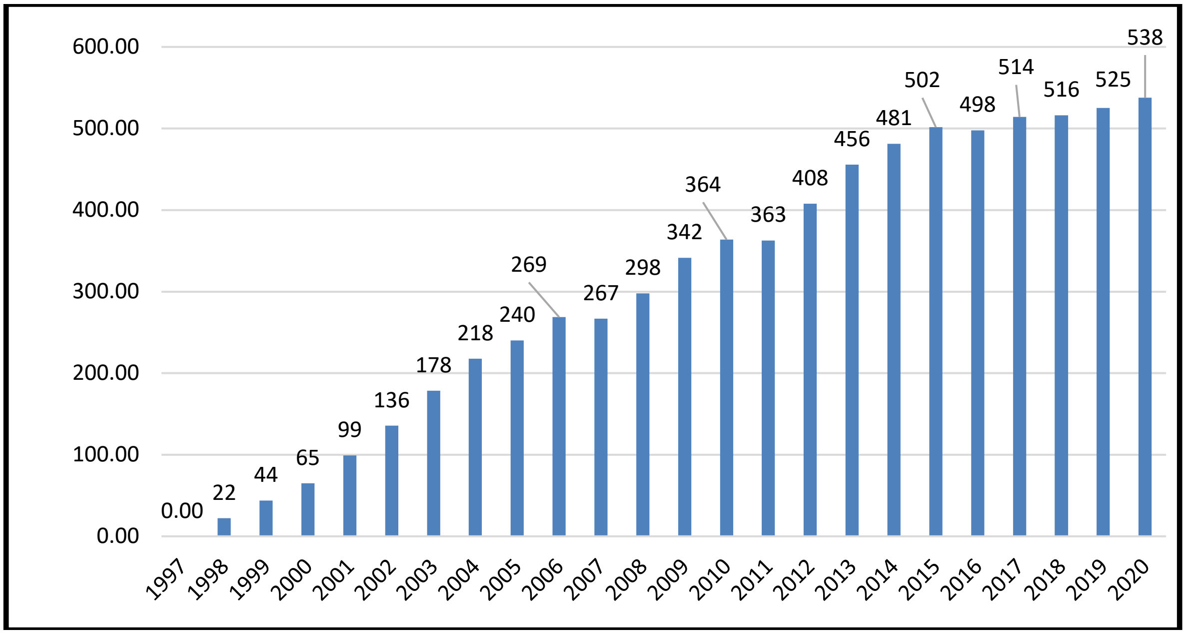


a) Fuel consumption

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%. 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 20% from 253 to 304.5 million litres/year between 1997 and 2020. This increase in aggregate fuel use reflects the 91.9% 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 2020 in the three southern states, an additional 2,749 million litres of fuel would have been used. At this level of fuel usage, an additional 7,341 million kg of carbon dioxide would otherwise have been released into the atmosphere (Figure 73).

Figure 73: Brazil soybeans permanent reduction in carbon dioxide emissions resulting from a reduction in fuel use 1996-2020 (million kg)

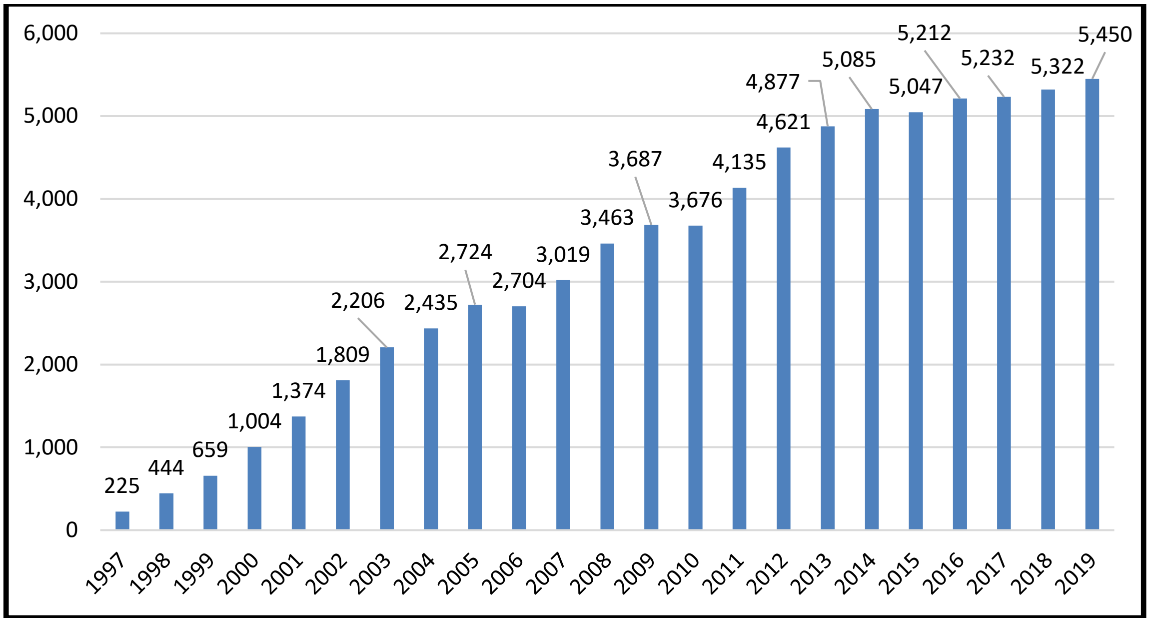


b) Soil carbon sequestration

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 20,275 million kg of carbon (equal to a saving of 74,409 million kg of carbon dioxide) has been retained in the soil that would otherwise have been released into the atmosphere (Figure 74).

Figure 74: Brazil soybeans - potential additional carbon dioxide sequestered 1996-2020 (million kg)



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 5.6 million ha between 1999 and 2020 (Paraguay 1.2 to 3.15 million ha, Uruguay 8,900 ha to 1.1 million ha and Bolivia 0.6 to 1.39 million ha) and the area of GM soybeans from 58,000 ha to 5.64 million ha.

a) Fuel consumption

Using the findings and assumptions applied to Argentina[103] (see above), the savings in fuel consumption for soybean production between 1999 and 2020 (associated with changes in NT/RT tillage systems, the adoption of GM HT technology and comparing the proportion of NT soybeans in 2020 with the 1999 level) has been 899 million litres. At this level of fuel saving, the reduction in the level of carbon dioxide released into the atmosphere has been 2,401 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 6,633 million kg of carbon. In terms of carbon dioxide emission this equates to a saving of 24,342 million kg of carbon dioxide that may otherwise have been released into the atmosphere.

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[103] 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.

4.2.4.5 Canada

During the period 1996 to 2008 period, tillage practices across the Canadian Prairies changed considerable with RT/NT increasing from 20% to 55% of the crop area. The introduction of GM HT soybeans in 1997 contributed to this transition, as well as, the doubling of the soybean crop area from 1.1 million ha in 1997 to 2 million ha in 2020. Within this, the NT soybean area increased from 0.2 million ha in 1997 to 1.1 million ha in 2020 whilst the RT area increased from 0.3 million ha to 0.35 million ha and the CT area increased from 0.5 million ha to 0.57 million ha.

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 2020 has been 255 million litres. At this level of fuel saving, the reduction in the level of carbon dioxide released into the atmosphere has been 681 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 971 million kg of carbon. In terms of carbon dioxide emission this equates to a saving of 3,563 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 24 years between 30.6 million ha (2001) and 37.9 million ha (2007); in 2020 it was 33.4 million ha. Over the 1997-2020 period[104], the maize area using CT with less than 15% crop residue fell by 75% (11.1 to 2.7 m ha), RT with between 15-30% crop residue increased by 55% (7.8 to 12.1 m ha) and the NT with crop residue in excess of 30% maize area increased by 39% (13.3 to 18.6 m ha) - Figure 75.

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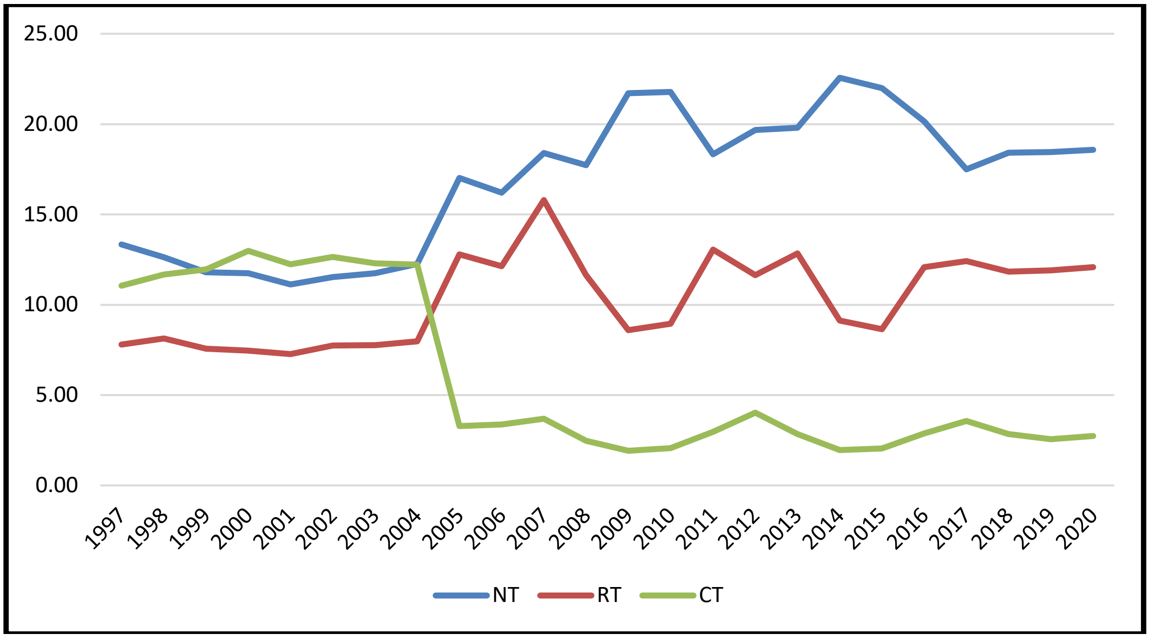
[104] GM HT maize was first planted commercially in the US in 1997. However, 1998 was the first year of widespread adoption of the technology

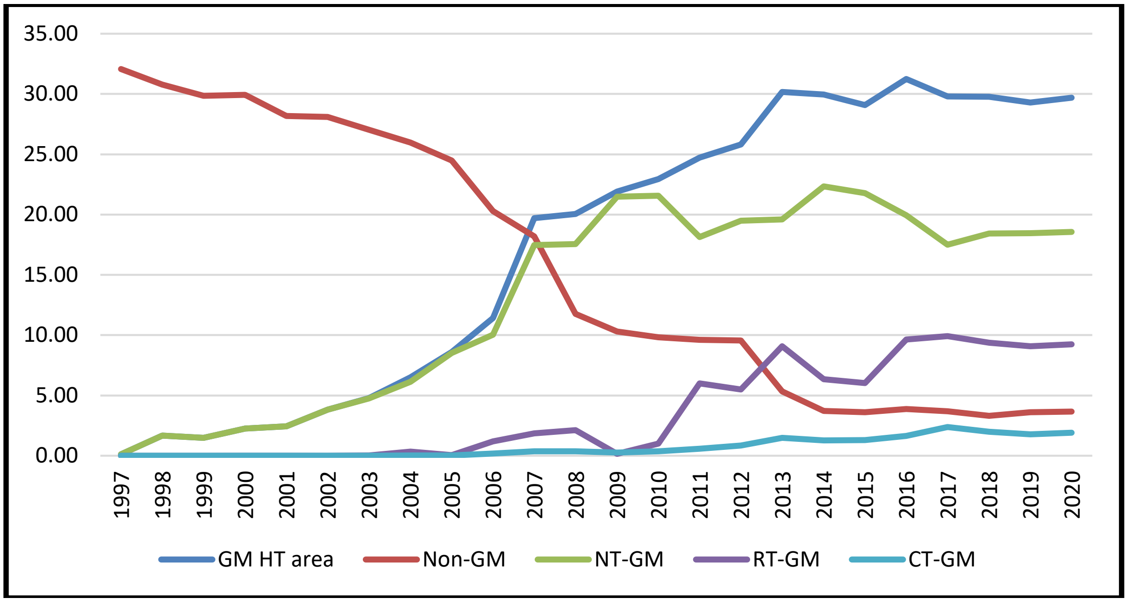
Figure 75: US maize: crop area by tillage practices 1996-2020 (million ha)



Adapted from Conservation Technology Information Center's (CTIC) National Crop Residue Management farm survey - https://www.ctic.org/CRM 1996-2004 & Operational Tillage Management System - https://www.ctic.org/OpTIS based on remote sensing data for top five cropping states - Illinois, Iowa, Nebraska, Indiana & Minnesota 2005-2020.

The most rapid rate of adoption of GM HT maize technology has been by growers using NT systems (GM HT cultivars has accounted for more than 90% of the total NT maize since 2006). This compares with CT systems for maize where GM HT cultivars account for 70% of total maize plantings in 2020 - Figure 76.

Figure 76: US GM HT maize by tillage 1996-2020 (million ha)

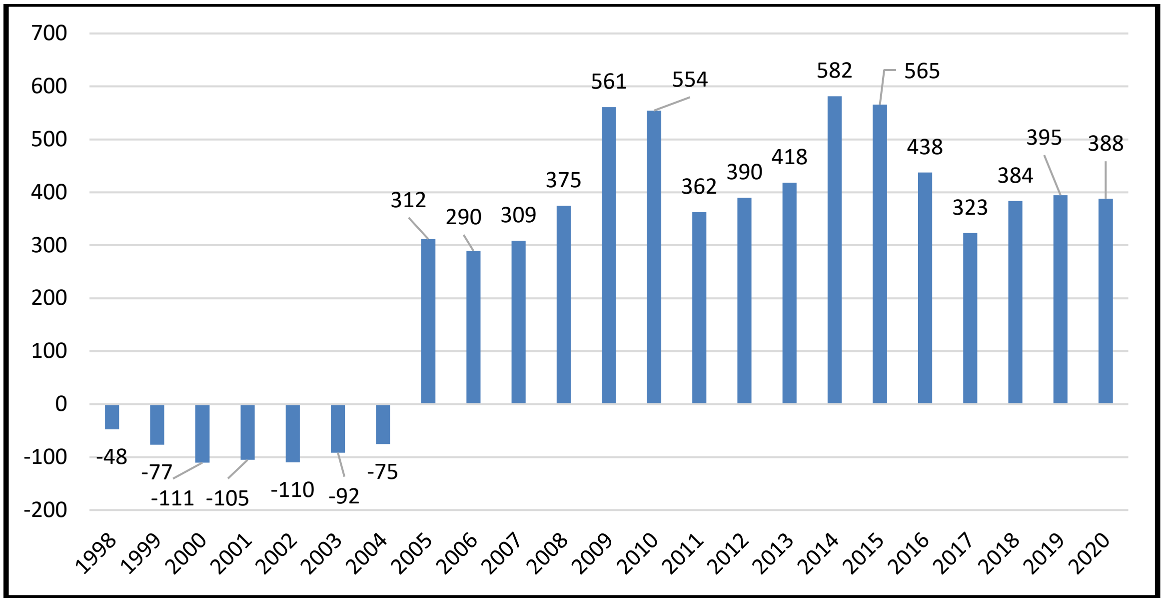


a) Fuel consumption

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 2020 has decreased by 6.9% (94.9 million litres). Over the same period, the area planted to maize increased by 3.7%, highlighting a fall in average fuel usage of 11% (from 42.6 litres/ha to 38.2 litres/ha). A comparison of GM HT versus conventional production systems shows that in 2020, the average tillage fuel consumption on the GM HT planted area was 36.9 litres/ha compared to 48.8 litres/ha for the conventional crop.

These changes to tillage fuel use and the resultant reduction on carbon dioxide emissions in US maize for the 1996-2020 period are summarised in (Figure 77). The negative data for the period 1998 to 2004 illustrate the increase in carbon dioxide emissions resulting from the marginal increase in the crop area. The cumulative permanent reduction in tillage fuel use in US maize is 2,257 million litres which equates to a reduction in carbon dioxide emission of 6,027 million kg.

Figure 77: US maize permanent reduction in carbon dioxide emissions resulting from a reduction in fuel use 1996-2020 (million kg)



Note: The negative data for the period 1998 to 2004 illustrate the increase in carbon dioxide emissions resulting from the marginal increase in the crop area and the proportion in CT.

b) Soil carbon sequestration

Based on and using estimates of the soil carbon sequestered by tillage system for maize and soybeans in continuous rotation, the maize 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)[105]. Based on these assumptions and using the crop area

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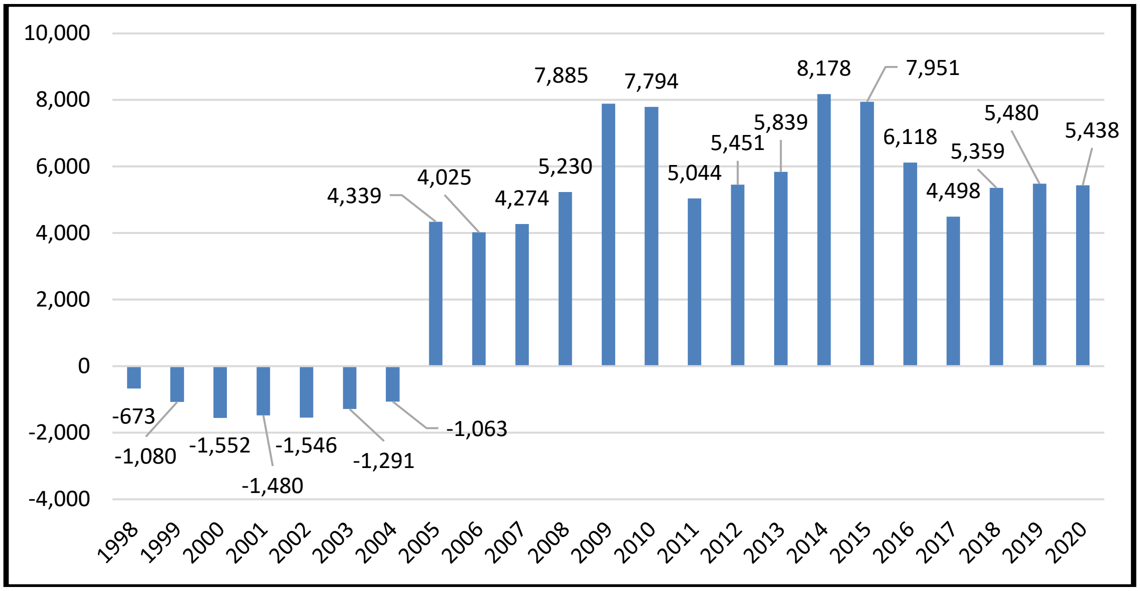
[105] The actual rate of soil carbon sequestered by tillage system is, however, dependent upon soil type, soil organic content, quantity and type of crop residue

planted by tillage system and type of seed planted (GM HT and conventional), our estimates of total soil carbon sequestered are:

- An increase of 1,630 million kg carbon/year (from 3,943 million kg in 1997 to 5,570 million kg carbon/year in 2020) due to a combination of an increase in the crop area and the NT/RT maize area;
- The average amount of carbon sequestered per ha increased by 37.8% from 122.5 in 1997 to 166.9 kg carbon/ha/year in 2020.

Cumulatively, since 1997 the increase in soil carbon due to the increase in RT and NT in US maize production systems has been 22,948 million kg of carbon which, in terms of carbon dioxide emissions, equates to a saving of 84,218 million kg of carbon dioxide that would otherwise have been released into the atmosphere (Figure 78 and Appendix 6). This estimate does not take into consideration the potential loss in carbon sequestration that might arise from a return to conventional tillage.

Figure 78: US maize - potential additional carbon dioxide sequestered 1996-2020 (million kg)



Note: The negative data for the period 1998 to 2004 illustrate the increase in carbon dioxide emissions resulting from the marginal increase in the crop area and the proportion in CT

4.2.5.2 Canada

Against the background of increasing adoption of NT and RT (see section 4.2.4.5) and a fluctuating maize area (1.4 million ha in 2020), the introduction and increasing adoption of GM HT maize technology (from 1999) has facilitated a significant increase in the NT maize area from 0.3 million ha in 1999 to 0.77 million ha in 2020.

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 2020 (associated with changes in RT/NT systems, the adoption of GM HT technology and comparing the proportion of NT maize in 2020 with the 1999 level) has been 121.1 million litres. This level of fuel saving is equal to a reduction in the level of carbon dioxide released into the atmosphere of 323 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 330 million kg of carbon. In terms of carbon dioxide emission savings, this equates to 1,213 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 increased due to the availability of GM HT maize because of a lack of relevant data. However, the following should be noted:

- in Argentina, GM HT maize was first available for use in 2004, but seed containing this trait did not account for more than 50% of the total crop until 2011 (98% of 2020 crop used the HT 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 (0.72 million ha in the US in 2020 compared to 8.3 million ha in Canada).

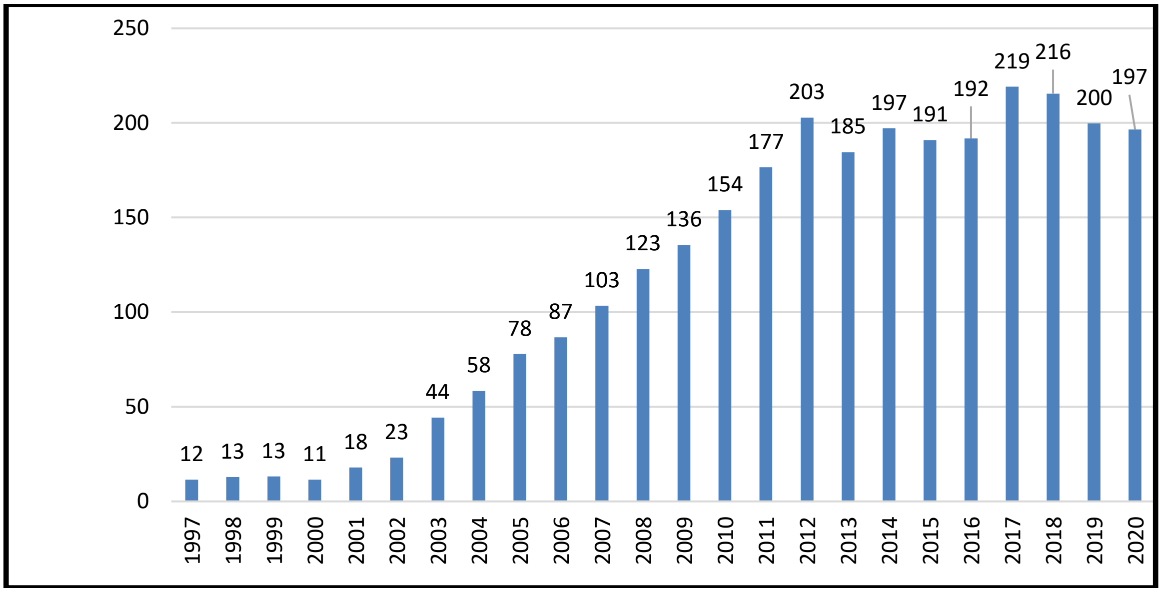
Research identified that included examination of the impact of using GM HT technology in canola on carbon emissions includes:

- Smyth *et al* (2011) which surveyed 600 canola farmers in the three main canola growing 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. 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 *et al* (2014) identified that conservation tillage, notably NT, became profitable and popular with the majority of Canadian arable farmers during and after the late 1990's 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 1996-2020 is 1,067 million litres, which equates to a reduction in carbon dioxide emissions of 2,848 million kg (Figure 79).

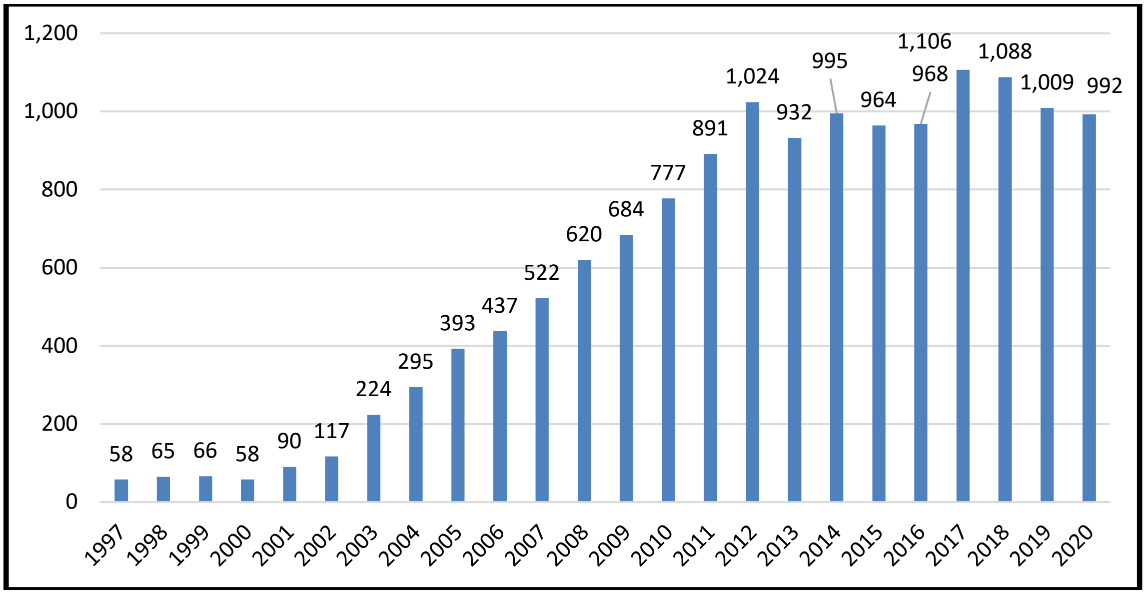
Figure 79: Canadian canola permanent reduction in carbon dioxide emissions resulting from a reduction in fuel use 1997-2020 (million kg)



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). Our analysis based on this research shows a cumulative increase in soil carbon storage, associated with RT and NT in Canadian canola production between 1996 and 2020, of 3,917 million kg of carbon, which in terms of carbon dioxide emissions, equates to a saving of 14,375 million kg of carbon dioxide that would otherwise have been released into the atmosphere (Figure 80). Additional information is also provided in Appendix 6. Readers should note these estimates are based on a soil sequestration rate of 55 kg carbon/ha/year which is significantly lower than the rate used in the US for maize (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.

Figure 80: Canadian canola - potential additional carbon dioxide sequestered 1997-2020 (million kg)



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, NT cotton accounted for only 18% of the crop area by 2015 (Claassen *et al* (2018)). 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 Conservation Tillage Study[106] (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 2020, the global cotton area planted with GM IR cultivars increased from 0.8 million ha to 23.2 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 India[107]) of GM IR cotton over the period 1996-2020, suggests that there has been a reduction of 339 million ha of cotton 'spray' area. The resulting cumulative saving in tractor fuel consumption has been 285 million litres. This represents a permanent reduction in carbon dioxide emissions of 760 million kg (Figure 81).

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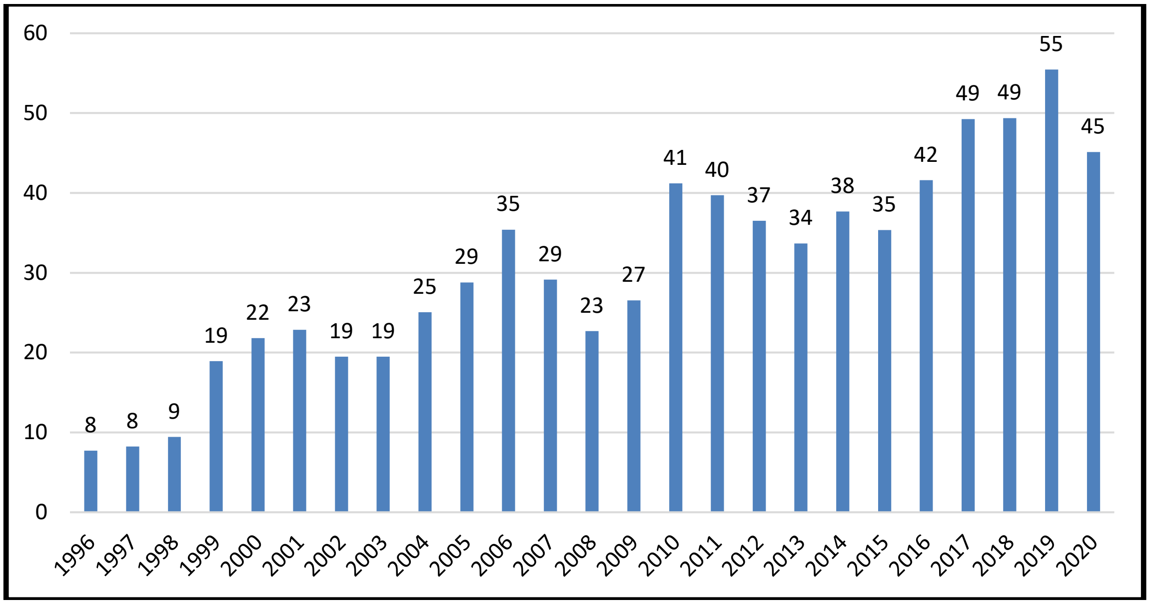
[106] https://slideplayer.com/slide/7861322/

[107] Excluded because all spraying is assumed to be undertaken by hand

Figure 81: Permanent reduction in global tractor fuel consumption and carbon dioxide emissions resulting from the cultivation of GM IR cotton (1996-2020)



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 439 million ha of maize being sprayed in the period 2008-2020, with a cumulative saving in tractor fuel of 369 million litres. This is equivalent to a permanent reduction in carbon dioxide emissions of 984 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 million ha (2020)) 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 2020 period of 108.2 million 'spray' ha. The resultant, cumulative saving in tractor fuel equates to 90.2 million litres, equivalent to a permanent reduction in carbon dioxide emissions of 243 million kg.

4.2.10 Insect resistant soybeans

IR soybean technology was first used commercially in South America in 2013, and in 2020 was planted on 29.5 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 period has, therefore been equal to 449 million litres, equivalent to a permanent reduction in carbon dioxide emissions of 1,199 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 2020 level of additional global maize production (47.9 million tonnes) due to GM cultivars, this additional production assimilated about 144 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, maize, 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* (2010[108]) have, however, concluded that intensification of agriculture leads to a net reduction in GHG 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; and
- Maintaining optimum nitrogen fertilisation is considered to be critical for maintaining or increasing the SOC in the Mid-West part of the US (Poffenbarger *et al* (2017)).

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) Reduced fuel use

The fuel savings arising from making fewer insecticide applications with the use of GM IR crop technology in maize, cotton and soybeans and the switch from CT to RT/NT systems facilitated by GM HT crops, have delivered permanent savings in carbon dioxide emissions. Over the period 1996 to 2020, the cumulative permanent reduction in fuel use has been about 39,147 million kg of carbon dioxide, arising from reduced fuel use of 14,662 million litres. In terms of car equivalents, this is equal to taking 25.9 million cars off the road for a year (Table 29).

The largest fuel use-related reductions in carbon dioxide emissions have come from the adoption of GM HT technology and how it has facilitated a switch to RT/NT production systems with their reduced soil cultivation practices. This accounted for 92% of the fuel and carbon dioxide savings in the period 1996-2020, within which GM HT soybeans accounted for the largest contribution (68% of the total savings). These savings have been greatest in South America.

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[108] Albeit examining the impact on GHG emissions from general intensification of agriculture between 1961 and 2005

In 2020, the fuel related savings were 2,330 million kg of carbon dioxide, arising from reduced fuel use of 948 million litres. These savings are equivalent to taking 1.68 million cars off the road for one year.

Table 29: Carbon storage/sequestration from reduced fuel use with GM crops 1996-2020

Crop/trait/country	**Fuel saving (million litres)**	**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)**
HT soybeans			
Argentina	4,433	11,837	7,844
Brazil	2,749	7,341	4,865
Bolivia, Paraguay, Uruguay	899	2,401	1,591
US	1,687	4,503	2,984
Canada	255	681	451
HT maize			
US	2,257	6,027	3,994
Canada	121	323	214
HT canola			
Canada: GM HT canola	1,067	2,848	1,887
IR maize			
Brazil	369	984	652
US/Canada/Spain/South Africa	91	243	161
IR cotton – global	285	760	504
IR soybeans – South America	449	1,199	795
Total	***14,662***	***39,147***	***25,942***

Notes:

1 Assumption: an average family car in 2020 produces 123.4 grams of carbon dioxide per km. A car does an average of 12,231 km/year and therefore produces 1,509 kg of carbon dioxide/year

2 GM IR cotton. India, Pakistan, Myanmar and China excluded because insecticides assumed to be applied by hand, using back pack sprayers

b) Additional soil carbon storage/sequestration

The widespread adoption and maintenance of RT/NT production systems in North and South America, has, as well as reducing tractor fuel use for tillage, enhanced soil quality and cut levels of soil erosion. In turn, more carbon has remained stored in the soil leading to lower emissions of carbon dioxide.

Based on the areas of GM HT crops using RT/NT production systems in North and South America in 2020, we estimate that an extra 5,750 million kg of soil carbon has been sequestered in 2020. This is equivalent to 21,101 million kg of carbon dioxide that has not been released into the global atmosphere. In terms of removing vehicles from the road, these savings are equivalent to taking 14 million cars off the road for one year (Table 30).

Table 30: Context of carbon sequestration impact 2020: car equivalents

Crop/trait/country	Additional carbon stored in soil (million kg of carbon)	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	1,832.5	6,725.2	4,445.8
Brazil	1,485.0	5,450.1	3,611.0
Bolivia, Paraguay, Uruguay	490.7	1,800.8	1,193.1
US	110.9	407.0	269.6
Canada	62.9	230.7	152.9
HT maize			
US	1,481.6	5,437.6	3,602.7
Canada	15.6	57.4	38.0
HT canola			
Canada: GM HT canola	270.4	992.4	657.5
IR maize			
Brazil	0	0	0
US/Canada/Spain/South Africa	0	0	0
IR cotton – global	0	0	0
IR soybeans – South America	0	0	0
Total	***5,749.6***	***21,101.1***	***13,980.7***

If the annual estimates of soil carbon sequestration are aggregated over the 1996-2020 period, then the additional amount of soil carbon sequestered since 1996 has been equivalent to 344,044 million kg of carbon dioxide that has not been released into the global atmosphere, equivalent to taking about 228 million cars off the road over this period. Readers should, however, note that this estimate is likely to significantly overstate the true soil carbon sequestration benefits from the adoption of RT/NT systems over this 24 year period because some of the additional soil carbon sequestration gains from RT/NT systems will have been lost from some subsequent ploughing of land in these crops and production systems.

Estimating these possible losses that may arise from subsequent ploughing would be complex and difficult to undertake. One study from the US (Claassen R et al (2018)) estimated that approximately 20% of the combined area of corn, soybeans, cotton and wheat in the USA were in continuous NT/RT production systems during the period 2012-2016. This factor should therefore be taken into account when using the estimates presented in this paper. In addition, it should be noted that soil carbon savings are based on savings arising from the rapid adoption of RT/NT farming systems, 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.

Overall, 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.

Returning to the 2020 analysis of carbon emission savings from both sources of fuel related savings and soil carbon storage, aggregating these benefits results in the total carbon dioxide savings in 2020 being equal to about 23,631 million kg, equivalent to taking 15.6 million cars off the road for a year. This is equal to 49% of registered cars in the UK.

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 (2020)

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	0.897	3,443	3,088	3,030	413	+10%	0.906	2,746	340
China	1.976	3,250	6,422	3,087	162	+10%	1.805	6,130	293

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 maize: 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)

	2007onward +18%	studies used all years to 2006. Thereafter based on Gonzales et al (2009)	+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 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 Weld (2009)	Gouse et al (2005), Gouse et al (2006 a) & b) reported yield impacts as shown (range of +11% to +32%), Van der Weld (2009)	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 comes 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) and Brookes (2019)	Sources as for cost of technology

Other EU	Portugal +12.5%	Impacts based on average of available impact data in each country	Based on Brookes (2008) and Brookes (2019) which drew on commercial trial and plot monitoring reported +12% in 2005 and between +8% and +17% in 2006	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, +11.1% 2013 onwards	Farmer surveys	Galvão A (2009, 2010, 2012, 2013, 2014, 2016)	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
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% 2007-2012, +16% onwards	Mendez et al (2011) and Brookes (2020)	Mendez et al (2011) farm survey from 2009. Brookes draws on 2015 and 2017 farmer surveys conducted by Celeres	Mendez et al (2011) and Brookes (2020)	Mendez et al (2011) and Brookes (2020)
Vietnam	+10.22%	Brookes (2017), Brookes and Dinh (2021)	Brookes (2017), Brookes and Dinh (2021)	Brookes (2017), Brookes and Dinh (2021)	Brookes (2017), Brookes and Dinh (2021)

GM IR maize (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 references cited	Sankala & Blumenthal (2003 & (2006) drew on earlier work from Carpenter and Gianessi (2002) in which they estimated the average 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	Data derived from the same sources referred to for yield and updated from 2008 based on industry sources (for the estimated share of the insect resistance trait in the total seed premia for stacked traited seed	As identified in yield study references and in subsequent years adjusted to reflect broad cost of 'foregone' insecticide use

			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		
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 significant average yield gain	Fitt (2001) Doyle (2005) James (2002) CSIRO (2005)	Data derived from the same sources referred to for yield covering earlier years of adoption, then CSIRO for later years. For 2006-2009 cost of technology values confirmed by personal communication from Monsanto Australia	Data derived from the same sources referred to for yield covering earlier years of adoption, then CSIRO for later years
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	Data derived from the same sources referred to for yield. Cost of technology all	Data derived from the same sources referred to for yield and cost of technology.

			average gain of +30% based on work by Elena (2001)	years based on industry sources	
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% 2013, +15.8% 2014 15% 2015, +10.54% 2016, +10.3% 2017 and 2018	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 traited seed sales	Data derived from the same sources referred to for yield.
India	+45% 2002 +63% 2003 +54% 2004 +64% 2005 +50% 2006 & 2007	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 &	Data derived from the same sources referred to for yield. 2007 onwards cost of technology based	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)

	+40% 2008, +35% 2009 & 2010, +30% 2011, +24% 2012 onwards		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)	on industry sources	
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 onwards +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	+36.3% 2002. 2009 onwards +20.7%	Farm survey 2007s, 2015 and 2017	Based on Zambrano P et al (2009) and Brookes (2020) – drawing on farm surveys by Celeres 2015 and 2017	Zambrano (2009), Brookes (2020)	Zambrano (2009), Brookes (2020)
Burkina Faso	+20 2008, +18.9% 2009 onwards	Trials 2008, farm survey 2009	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)
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: 1st generation	Nil	Not relevant	Not relevant	Marra et al (2002) Carpenter & Gianessi (2002) Sankala & Blumenthal (2000 & 2006)	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	Johnson S & Strom S (2008) & updated post 2008 to reflect herbicide price and common product usage
Canada: 1st 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: 2nd generation	+5% 2009 and 2010, +10.4% 2011, +11.2% 2012, +11% 2013, +9% 2014 onwards 8.9%	Farm level monitoring and farmer feedback	Monsanto farmer surveys (annual)	Industry estimates of seed premia relative to 1st generation GM HT seed	as 1st generation
Argentina	Nil but second crop benefits	Not relevant except 2nd crop – see separate table	Not relevant	Qaim & Traxler (2005), Trigo & CAP (2006) and 2006 onwards (Monsanto royalty rate)	Qaim & Traxler (2005), Trigo & CAP (2006), Rodriguez et al (2021) & 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 (2004). Also agreed royalty rates from 2004 applied to all years to 2006. 2007 onwards based on Galvão (2009, 2010, 2012, 2013 and 2015)	Sources as in cost of technology
Paraguay	Nil but second crop benefits	Not relevant except 2nd crop	Not relevant	As Argentina: no country-specific analysis identified. Impacts confirmed from industry sources (annual personal communications	As Argentina – herbicide cost differences adjusted post 2008 based on industry sources and AMIS Global, Kleffmann herbicide usage data 2011, 2013, 2015, 2016

				2006-2012). Seed cost based on royalty rate since 2007	
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/Kleffmann herbicide usage data 2011, 2013, 2015, 2016
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/Kleffmann herbicide usage data 2011, 2013, 2015, 2016
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, -1.87% 2016	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 1999-2003 (note not grown in 2007) plus 2006 farm survey	For previous year – based on Brookes (2005) – the only published source identified. Also, Monsanto Romania (2007)	Brookes (2005) Monsanto Romania (2007)	Brookes (2005) 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,	Farm trials and post market	Monsanto farm trials and commercial crop monitoring (surveys)	As yield source and Kleffmann	As yield source and Kleffmann

	9.4% 2015 onwards	monitoring survey			
Argentina	+9.1% 2013, +7.8% 2014, 7.1% 2015 onwards	As Brazil	Monsanto farm trials and commercial crop monitoring (surveys)	As yield source and Kleffmann	As yield source and Kleffmann
Paraguay	+12.8% 2013, +11.9% 2014, 9.1% 2015, 12.3% 2016, 11.5% 2017 and 2018	As Brazil	Monsanto farm trials and commercial crop monitoring (surveys)	As yield source	As yield source and Kleffmann
Uruguay	+8.8% 2013, +7.8% 2014, 7% 2015 onwards	As Brazil	Monsanto farm trials and commercial crop monitoring (surveys)	As yield source	As yield source and Kleffmann
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% -	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

		industry analysis (note no significant plantings until 2006)			
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 onwards	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), Brookes (2020)	Mendez et al (2011) farm survey from 2009 and Celeres farmer surveys 2015 and 2017 (see Brookes 2020)	Mendez et al (2011), Brookes (2020)	Mendez et al (2011), Brookes (2020)
Uruguay	Zero	Not relevant	Not relevant	No studies available – based on Argentina	No studies available – based on Argentina plus annual AMIS Global/Kleffmann 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/Kleffmann herbicide use data
Vietnam	+5%	Brookes (2017)	Brookes (2017)	Brookes (2017)	Brookes (2017)

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 traited 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 0% 2008, +5.11% 2009, +18.1%	Based on annual monitoring reports to Ministry of Agriculture by	Same as source for cost data	No published studies identified - based on personal communications with Monsanto	No published studies identified - based on annual personal communications with Monsanto Mexico and their annual reporting

	2010, +5.1% 2011, +13.1% 2012, +14.2% 2013, +13.3% 2014, +19.6% 2015 and 2016, +16% 2017-20	Monsanto Mexico		Mexico and their annual reporting	
Colombia	+4%	Brookes (2020)	Brookes (2020)	Brookes (2020)	Brookes (2020)
Brazil	+2.35% 2010 +3.1% 2011, -1.8% 2012, +1.6% 2013, +1.6% 2014 onwards	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 2004; for GM glyphosate tolerant varieties no yield difference 2004, 2005, 2008, 2010	After 2004 based on differences between average annual variety trial results for Clearfields (non GM herbicide	Same as for cost data	Based on Canola Council (2001) to 2003 then adjusted to reflect main current non GM (HT) alternative of 'Clearfields' – data derived from personal communications with the Canola	Based on Canola Council (2001) to 2003 then 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) which includes spillover benefits of $ Can13.49 to

	+4% 2006 and 2007, +1.67% 2009, +1.6% 2011, +1.5% 2012, +3.1% 2013, +3.4% 2014, +4.3% 2015, +2.6% 2016 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, +7.3% 2016	tolerant varieties) and GM alternatives. GM alternatives differentiated into glyphosate tolerant and glufosinate tolerant		Council (2008) plus Gusta M et al (2009)	follow on crops – applied from 2006. Also adjusted annually to reflect changes in typical herbicides used on different crops (GM HT, conventional, Clearfields)
Australia	+21.08% 2008, +20.9% 2009, +15.8% 2010, +7.6% 2011 and 2012, +11% 2013-2015, +8% 2016 onwards	Survey based with average yield gain based on weighting yield gains for different types of seed by seed sales or number of farmers using different seed types	Based on survey of licence holders by Monsanto Australia, Fischer and Tozer (2009) and Hudson and Richards (2014)	Sources as for yield changes	Sources as for yield changes
GM HT sugar beet					
US & Canada	+12.58% 2007	Farm survey & extension	Kniss (2008) Khan (2008)	Kniss A (2008) Khan M (2008),	Kniss A (2010) Khan M (2008), Jon-Joseph A and Sprague C

	+2.8% 2008 +3.3% 2009-2012, +3.1% 2013, +3.2% 2014, +3.55% 2015, +3.58% 2016, +3.25% 2017 and 2018	service analysis			(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 1996-2020 (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	0.20	127.20	25.4
1998	0.35	125.24	43.8
1999	0.95	122.76	116.6
2000	1.15	125.38	144.2
2001	2.2	124.00	272.8
2002	2.6	143.32	372.6
2003	2.75	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	4.9	229.36	1.133.6
2008	3.35	224.87	754.1
2009	3.55	207.24	735.7
2010	4.4	257.69	1,133.8
2011	4.6	257.40	1,184.0
2012	3.22	291.00	938.6
2013	3.0	289.80	879.4
2014	4.0	195.91	777.1
2015	3.65	168.81	616.4
2016	4.15	153.75	637.8
2017	4.02	164.40	660.4
2018	4.6	154.19	713.1
2019	5.37	323.80	1,738.1
2020	5.27	269.80	1,422.4

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
Option 1		
Glyphosate	1.30	19.93
2 4 D	0.64	9.79
Flumioxazin	0.07	1.68
Chlorimuron	0.02	0.38
Lactofen	0.22	6.28
Clethodim	0.16	2.67
Total	**2.42**	**40.72**
Option 2		
Glyphosate	1.30	19.93
2 4 D	0.64	9.79
Flumioxazin	0.07	1.74
Chlorimuron	0.02	0.38
Thifensulfuron	0.01	0.11
Fomesafen	0.29	7.13
Clethodim	0.16	2.67
Total	**2.49**	**41.79**
Option 3		
Glyphosate	1.30	19.93
2 4 D	0.64	9.79
Sulfentrazone	0.20	2.39
Cloransulam	0.03	0.39
Clethodim	0.16	2.89
S Metalochlor	1.43	31.46
Total	**3.75**	**66.62**

US Soybeans: typical herbicide regimes for conventional no tillage production systems: South

	Active ingredient (kg/ha)	Field EIQ/ha value
Option 1		
Glyphosate	1.13	17.35
2 4 D	0.64	9.79
Flumioxazin	0.07	1.72
Metalochlor	1.36	29.97
Fomesafen	0.30	7.32
Clethodim	0.16	2.67
Total	**3.66**	**68.82**
Option 2		
Glyphosate	1.13	17.35
2 4 D	0.64	9.79
Flumioxazin	0.09	2.07
Chlorimuron	0.02	0.47
Fomesafen	0.37	9.03
Clethodim	0.16	2.67
Total	**2.41**	**41.37**

Option 3		
Glyphosate	1.13	17.35
2 4 D	0.64	9.79
Metalochlor	1.36	29.97
Fomesafen	0.30	7.32
Aciforen	0.30	7.13
S Metalochlor	1.32	29.09
Clethodim	0.11	1.91
Total	**5.17**	**102.56**

US Soybeans: typical herbicide regimes for conventional crop and tillage production systems: South

	Active ingredient (kg/ha)	**Field EIQ/ha value**
Option 1		
Flumioxazin	0.07	1.68
Metalochlor	1.32	29.11
Fomesafen	0.29	7.10
Clethodim	0.16	2.67
Total	**1.84**	**40.60**
Option 2		
Flumioxazin	0.07	1.68
Chlorimuron	0.02	0.38
Fomesafen	0.29	7.13
Clethodim	0.16	2.67
Total	**0.54**	**11.85**
Option 3		
Metalochlor	1.36	29.97
Fomesafen	0.30	7.32
Aciforen	0.30	7.13
S Metalochlor	1.43	31.46
Clethodim	0.11	1.73
Total	**3.51**	**77.88**

Weighted average all by tillage types: ai/ha 2.78 kg/ha, EIQ/ha 54.66

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 2020

	Active ingredient (kg/ha)	**Field EIQ/ha value**
GM HT soybean	3.59	54.53
Source: Kleffmann dataset on pesticide use 2018/19		
Conventional soybean		
Option 1		
Glyphosate	2.27	34.80
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	**3.02**	**49.06**
Option 2		
Glyphosate	2.27	34.80
Dicamba	0.12	3.04
Acetochlor	1.35	26.87
Haloxifop	0.18	4.00
Sulfentrazone	0.19	2.23
Total	**4.11**	**70.92**
Option 3		
Glyphosate	2.27	34.80
Atrazine	1.07	24.50
Bentazon	0.60	11.22
2 4 D ester	0.4	6.12
Imazaquin	0.024	0.37
Total	**4.36**	**77.01**
Option 4		
Glyphosate	2.27	34.80
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	**3.15**	**54.54**
Option 5		
Glyphosate	2.27	34.80
Metsulfuron	0.03	0.50
2 4 D amine	0.8	16.56
Imazethapyr	0.1	1.96
Haloxifop	0.18	4.00
Total	**3.38**	**57.82**
Option 6		
Glyphosate	2.27	34.80
Metsulfuron	0.03	0.50
2 4 D amine	0.8	16.56
Imazethapyr	0.1	1.96
Clethodim	0.24	4.08

Total	**3.44**	**57.90**
Average all six conventional options	**3.577**	**61.21**
Weighted average	**3.616**	**62.04**

Sources: AAPRESID, Kleffmann/Kynetec, Bayer Argentina

Weights (based on expected usage): option 1 10%, options 2 to 5 17.5% each, option 6 20%

GM HT versus conventional maize Argentina 2020

	Active ingredient (kg/ha)	**Field EIQ/ha value**
Conventional		
Option 1		
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**
Option 2		
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**	**73.61**
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, Kleffmann and Monsanto/Bayer Argentina

Typical herbicide regimes for GM HT soybeans Brazil 2020

Active ingredient	**Amount (kg/ha of crop)**	**Field EIQ/ha**
Burndown (applicable to conventional and GM HT)	2.41	39.72
GM HT over the top	0.69	9.23
GM HT total	**3.10**	**48.95**
Conventional over the top	0.75	15.0
Conventional total	**3.16**	**54.72**

Source: derived from Kleffmann & AMIS Global

Typical herbicide regimes for GM HT soybean in South Africa 2020

Active ingredient	**Amount (kg/ha of crop)**	**Field EIQ/ha**
Conventional soybean		
Option one		
Metalochlor	1.18	25.96
Metribuzin	1.59	45.11
Total	**2.77**	**71.07**
Option two		
S Metolachlor	0.92	20.84

Dimethenamid	1.05	12.62
Total	**2.97**	**32.86**
Option 3		
S Metolachlor	0.92	20.24
Mesotrione	0.18	3.36
Total	**1.10**	**23.60**
Weighted average	**1.95**	**42.51**
GM HT soybean – based on AMIS Global 2015	**1.68**	**28.73**

Source: Monsanto/Bayer South Africa, AMIS Global, Kleffmann

Note conventional weighted average, weighted by use – option 1, 70%, option 2, 20%, option 3, 10%

Typical herbicide regimes for GM HT maize in Canada 2020

Active ingredient	**Amount (kg/ha of crop)**	**Field EIQ/ha**
Conventional maize		
S Metalochlor	1.30	28.60
Atrazine	1.09	24.96
Mesotrione	0.12	2.22
Dicamba	0.46	12.11
Total	**2.97**	**67.89**
GM glyphosate tolerant maize		
S Metalochlor	0.871	19.16
Atrazine	0.73	16.72
Glyphosate	1.21	18.55
Total	**2.81**	**54.44**
GM glufosinate tolerant maize		
S Metalochlor	0.871	19.16
Atrazine	0.73	16.72
Glufosinate	0.37	7.49
Total	**1.971**	**43.38**

Sources: Weed Control Guide Ontario – annually updated, industry personal communications (various)

Typical insecticide regimes for cotton in India 2020

Active ingredient	**Amount (kg/ha of crop)**	**Field EIQ/ha**
Conventional cotton		
Option 1		
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	0.02	0.29
Total	**1.92**	**79.22**
Option 2		
Imidacloprid	0.06	2.2
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.45

Novaluron	0.02	0.29
Chloripyrifos	0.39	10.58
Profenfos	0.81	48.28
Metaflumizone	0.03	0.82
Emamectin	0.01	0.29
Total	**1.42**	**65.58**
Average conventional	**1.67**	**72.40**
Weighted average conventional	**1.72**	**73.76**
GM IR cotton		
Imidacloprid	0.06	2.2
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.45
Novaluron	0.02	0.29
Buprofezin	0.07	2.55
Acephate	0.63	15.79
Total	**0.89**	**23.95**
Option 2		
Imidacloprid	0.06	1.54
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	2.30
Novaluron	0.02	0.29
Total	**0.18**	**5.61**
Average GM IR cotton	**0.53**	**14.78**
Weighted average conventional	**0.604**	**16.61**
Difference GM versus conventional	**1.12**	**57.15**

Source: Bayer India, AMIS Global/Kynetec

Note weighted average for GM IR cotton based on insecticide usage – option 1 60%, option 2 40%

Typical insecticide regimes for cotton in China 2020

Active ingredient	**Amount (kg/ha of crop)**	**Field EIQ/ha**
Conventional cotton		
Imidacloprid	0.162	5.95
Abamectin	0.032	1.11
Chlorpyrifos	0.64	17.18
Deltamethrin	0.068	1.93
Phoxim	0.89	22.25
Lambda cyhalothrin	0.105	4.99
Profenphos	0.84	50.0
Total	**2.737**	**103.41**
GM IR cotton		
Imidacloprid	0.108	3.96
Abamectin	0.032	1.11
Chlorpyrifos	0.448	12.03
Deltamethrin	0.034	0.96
Phoxim	0	0
Lambda cyhalothrin	0.105	4.99
Profenphos	0.84	50.0
Total	**1.567**	**73.02**

Sources: Monsanto/Bayer China, AMIS Global, Kleffmann, Plant Protection Institute of the Chinese Academy of Agricultural Sciences

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 (l = 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*: l-2 weeks- 1, 2-4 weeks- 3, > 4 weeks – 5, pre-emergent herbicides – l, post-emergent herbicides – 3
- *Soil Residue Half-life:* Tl/2 <30 days – 1, Tl/2=30-100 days – 3, Tl/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);

EIQ Field Use Rating = EIQ x % active ingredient x 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 poor 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 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 Pg[109] (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 *et* al (1998) 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 period of 25-50 years 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 organic carbon storage (i.e. an increase of soil organic carbon) and soil organic carbon sequestration through the removal of atmospheric carbon dioxide. These include:

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- 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.

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[109] 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. Chenu *et al* (2018) discuss in detail the knowledge gaps and potential to increase organic carbon stocks, for example how can we increase carbon stocks, at which rate and for how long, where do we prioritize SOC storage, how do we estimate the potential gain and what agricultural practices should we implement?

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) including roots and associated mycorrhizea;
- Organic carbon mineralization (soil carbon outputs); and
- Soil erosion and re-deposition on soil organic gains and losses.

There is general agreement that the technical potential for sequestration of carbon in soil is significant but there are differences on the magnitude of the potential. Zomer *et al* (2017) estimate that croplands worldwide could sequester between 0.90 and 1.85 Pg C/yr, equivalent to 26-53% of the target of the "4p1000 Initiative: Soils for Food Security and Climate"[110]. However, there are often significant limitations to achieving the potential by location and within specific farming systems, including a lack of biomass and other inputs. Efforts to sequester carbon should concentrate on soils that have become degraded due to long periods of intensive arable cropping in temperate climatic regions in Asia, Europe and North America (van Groenigen *et al* (2017)).

A number of researchers have examined issues relating to carbon sequestration and different tillage systems and the following are of note:

- Buragiene *et al* (2019) reviewed different tillage technologies and their effect on carbon dioxide emissions from the soil. Their research concluded that deep ploughing immediately increases carbon dioxide emissions up to seven times higher that NT;
- Mangalassery *et al* (2014) analysed the greenhouse gas (GHG) balance for the carbon dioxide, methane and nitrous oxide emissions for conventional tillage and zero tillage systems. This research concluded that the net global warming potential under conventional tillage systems was 26%-31% higher than zero tillage. Although nitrous oxide emissions increased under zero tillage this was counter-balanced by a significant reduction in potential carbon dioxide and methane emissions which is closely linked to the geometry of the soil porous architecture;
- Nicoloso & Rice (2019) undertook a global meta-analysis assessing carbon and nitrogen storage and sequestration in no-till soils from the most important agricultural regions of the world. Their study identified that NT soils store both **more** carbon and nitrogen (up to 100 cm depth) than tilled soils. However, carbon sequestration depended on; an

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[110] 4p1000 - The aim of the initiative is to demonstrate that agriculture, and in particular agricultural soils can play a crucial role where food security and climate change are concerned. https://www.4p1000.org/

increase in crop frequency (eg. the rapid replanting of arable land following harvest); additional nitrogen inputs applied to each crop to ensure crop establishment; and decreased soil disturbance. Single cropping with land left fallow between harvesting and reseeding lacks carbon inputs to maintain soil carbon throughout the soil profile. The use of legumes alleviates nitrogen losses and supply extra nutrient to support carbon sequestration. Their findings indicate that no-till can effectively mitigate climate change by either avoiding CO_2 emissions from tilled soils or by promoting soil carbon sequestration in intensified agricultural systems;

- West & Marland (2003) estimated that the net carbon flux from the conversion from CT to NT was a decrease of 468 kg/carbon/ha/yr for maize, 32 kg/carbon/ha/yr for wheat and 371 kg/carbon/ha/yr for soybeans released to the atmosphere;
- West & Post (2002). This work analysed 67 long-term agricultural experiments, consisting of 276 paired treatments. These results indicate, on average, that a change from CT to 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 maize - 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/year[111];
- Ogle *et al* (2005) reviewed the impact of CT compared with NT in different climatic environments. They found that converting from CT to NT over a twenty-year period resulted in an increase in SOC storage of 23% in tropical moist climates, 17% in tropical dry climates, 16% in temperate moist and 10% in dry climatic conditions;
- Huggins *et al* (2007) assessed over a 14-year period crop sequence and tillage effect on SOC dynamics and storage, in continuous maize or soybeans and alternating maize-soybeans under different tillage treatments. CT soybeans and fallow decreased SOC at an average annual loss of 3.7 Mg/carbon/ha/yr, while chisel plough (RT) with continuous maize or maize-soybeans and NT with continuous maize, averaged an annual loss of 1.6 Mg/carbon/ha/yr. They concluded that without large additional carbon inputs (eg, manures, cover crops, perennial crops) the potential to approach SOC levels of native sites is limited with annual cropping and RT;
- 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 NT the average

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[111] Conversion factor for carbon sequestered into carbon dioxide = 3.67.

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 maize 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;
- 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;
- Haruna & Nkongolo (2019) reviewed the rate of change in soil organic matter (SOM) for maize and soybeans with and without cover crops under CT vs NT. NT resulted in 4% higher SOM and 8% higher SOM with a cover crop;
- Bernoux *et al* (2006) reviewed cropping systems, carbon sequestration and erosion in Brazil. Over 30 years of NT 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 *et al* (2000) and Sexstone *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 NT system (with liming) and minus 20 grams/ha/year for a NT system (without liming). The major factors influencing the beneficial effect of NT over CT 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 CT 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 (2009). They studied the GHG emission associated with N_2 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 N_2O emissions in comparison to CT, because in the CT system, harvest residue is incorporated into the soil during ploughing (increasing N_2O emissions);

- Omonode *et al* (2011) assessed N_2O emissions in maize following three decades of different tillage and rotation systems. Seasonal cumulative N_2O 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) 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. This work questioned the premise that NT leads to positive carbon sequestration compared to CT. 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 & Eriksen-Hamel (2008) and Blanco-Canqui & Lal R. (2007) 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 & 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, 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;
- Kong & Six (2010) researched the relative importance of crop roots compared with crop residue eg stalks, leaves etc. Their analysis demonstrated that at the end of the maize growing season, 52% of the root-derived carbon was still present in the soil, while only 4% of crop residue-derived carbon remained. These results suggest that root carbon contributes more to overall carbon stabilization than crop residue carbon;

- Al-Kaisi *et al* (2005) evaluated the effects of different tillage systems on soil organic carbon (SOC) and nitrogen (SON), residue carbon and nitrogen inputs and crop (maize and soybean) yields in Iowa. Yields of both maize 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 maize-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 maize and soybean in rotation that had been in NT cultivation for over 14 years. The carbon sink when planted with maize was 576 g C m^{-2} per year and soybean 33 g C m^{-2} per year. Accounting for 100% grain consumption, maize acts as a C-sink of 184 g C m^{-2} per year while soybean becomes a C-source of 94 g C m^{-2} per year. As these crops are generally grown in rotation, this system is a net sink of 90 g C m^{-2} 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) estimated that if the total area of maize/soybeans in the US converted to NT, 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 US carbon emissions at that time;
- 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)); and
- Walia *et al* (2017) examined in southern Illinois the tillage and fertiliser use effects on bulk density and soil carbon concentrations over a 44-year period (20 years in continuous maize and 24 years in maize–soybean rotation). NT management increased carbon stocks compared to tillage for depths of between 0 to 15 cm. NT combined with NPK (nitrogen, phosphorus and potassium) fertiliser maintained greater cumulative soil carbon stocks to 1 metre soil depth than either undisturbed forest soils or restored prairie soils. Additionally, NT/NPK had a maximum soil carbon increase over time of 360 kg carbon/ha/year for the top 15 cm over 44 years.

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.

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.

Lastly, Olge *et al* (2019) explored literature relating to the adoption of NT management, carbon storage and the 4 per mille (4p1000) initiative promoted through the UN Framework Convention on Climate Change. The research concluded that SOC storage can be higher under NT management in some soil types and climatic conditions even with redistribution of SOC, and contribute to reducing net greenhouse gas emissions. However, *uncertainties* tend to make this approach less attractive as a contributor to *stabilise* the climate system compared to other options. This research concluded that the adoption of NT may be better viewed as a method of:

- Reducing soil erosion;
- Adapting to climate change;
- Ensuring food security; and
- Valuing any increase in SOC storage as a "co-benefit[112]" for society in terms of reducing greenhouse gas emission.

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[112] Co-benefits of climate change mitigation as defined in the 4th Assessment Report of the Intergovernmental Panel on Climate Change are the positive benefits related to the reduction of greenhouse gases

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 CT 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.

Appendix 6: Additional carbon sequestration impact data

US soybeans: potential additional soil carbon sequestration (1996 to 2020)

	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	38.34	140.70
1998	2.8	29.1	80.93	297.02
1999	3.3	29.8	99.20	364.07
2000	5.2	30.1	156.72	575.18
2001	8.9	30.0	265.69	975.08
2002	10.0	29.5	296.63	1,088.65
2003	11.1	29.7	328.58	1,205.88
2004	10.9	30.3	328.68	1,206.27
2005	9.0	28.9	259.54	952.50
2006	5.3	30.6	162.98	598.13
2007	14.1	25.8	362.00	1,328.53
2008	3.9	30.2	118.43	434.63
2009	5.8	30.9	178.52	655.17
2010	11.5	31.6	363.72	1,334.86
2011	11.5	30.1	346.34	1,271.05
2012	10.7	30.8	328.84	1,206.86
2013	21.6	30.7	662.98	2,433.14
2014	10.4	33.4	346.53	1,271.76
2015	12.2	33.1	405.15	1,486.89
2016	6.2	33.5	206.14	756.53
2017	8.0	36.2	291.08	1,068.25
2018	3.5	35.7	126.21	463.17
2019	3.7	30.3	113.56	416.76
2020	3.3	33.3	110.90	406.99
Total			**5,977.68**	**21,938.05**

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

Argentine soybeans: potential additional soil carbon sequestration (1996 to 2020)

	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		5.91	-	-
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	111.28	19.75	2,197.86	8,066.14
2014	105.28	19.78	2,082.52	7,642.84
2015	105.28	19.40	2,042.51	7,496.01
2016	103.28	18.60	1,921.08	7,050.37
2017	101.28	16.30	1,650.93	6,058.91
2018	99.28	16.58	1,645.72	6,039.79
2019	107.28	16.72	1,793.94	6,583.76
2020	111.28	16.47	1,832.48	6,725.21
Total			**32,693.50**	**119,985.15**

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

US maize: potential additional soil carbon sequestration (1997 to 2020)

	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	-5.7	32.4	-183.41	-673.13
1999	-9.4	31.3	-294.20	-1,079.72
2000	-13.1	32.2	-422.85	-1,551.87
2001	-13.2	30.6	-403.30	-1,480.12
2002	-13.2	31.9	-421.26	-1,546.04
2003	-11.1	31.8	-351.70	-1,290.73
2004	-8.9	32.5	-289.56	-1,062.68
2005	35.7	33.1	1,182.31	4,339.09
2006	34.6	31.7	1,096.74	4,025.05
2007	30.7	37.9	1,164.52	4,273.78
2008	44.8	31.8	1,425.16	5,230.35
2009	66.7	32.2	2,148.54	7,885.12
2010	64.8	32.8	2,123.58	7,793.55
2011	40.0	34.4	1,374.40	5,044.06
2012	42.0	35.4	1,485.39	5,451.39
2013	44.8	35.5	1,591.05	5,839.16
2014	66.2	33.6	2,228.31	8,177.91
2015	66.3	32.7	2,166.55	7,951.23
2016	47.5	35.1	1,666.96	6,117.73
2017	36.6	33.5	1,225.70	4,498.33
2018	44.1	33.1	1,460.15	5,358.74
2019	45.4	32.9	1,493.05	5,479.51
2020	44.4	33.4	1,481.63	5,437.57
Total			**22,947.76**	**84,218.29**

Assumption: carbon sequestration remains at the 1997 level of 122.5 kg carbon/ha/year

Canadian canola: potential additional soil carbon sequestration (1996 to 2020)

	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
2016	32.5	8.1	263.87	968.39
2017	32.5	9.3	301.37	1,106.04
2018	32.5	9.1	296.40	1,087.79
2019	32.5	8.5	274.82	1,008.59
2020	32.5	8.3	270.40	992.37
Total			**3,916.91**	**14,375.06**

Notes: NT/RT = +55 kg of carbon/ha/yr CT = -10 kg of carbon/ha/yr

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