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RESEARCH PAPER

Environmental impacts of genetically modified (GM) crop use 1996-2016: Impacts on pesticide use and carbon emissions

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ABSTRACT. This paper updates previous assessments of the environmental impacts associated with using crop biotechnology in global agriculture. It focuses on the environmental impacts associated with changes in pesticide use and greenhouse gas emissions arising from the use of GM crops since their first widespread commercial use over 20 years ago. The adoption of GM insect resistant and herbicide tolerant technology has reduced pesticide spraying by 671.4 million kg (8.2%) and, as a result, decreased the environmental impact associated with herbicide and insecticide use on these crops (as measured by the indicator, the Environmental Impact Quotient (EIQ)) by 18.4%. The technology has also facilitated important cuts in fuel use and tillage changes, resulting in a significant reduction in the release of greenhouse gas emissions from the GM cropping area. In 2016, this was equivalent to removing 16.7 million cars from the roads.

KEYWORDS. active ingredient, biotech crops, carbon sequestration, environmental impact quotient, GMO, no tillage, pesticide

INTRODUCTION

GM crop technology has been widely used for over 20 years in a number of countries and is mainly found in the four crops of canola, maize, cotton and soybean. In 2016, crops containing this type of technology accounted for 48% of the global plantings of these four crops. In addition, small areas of GM sugar beet (adopted in the USA and Canada since 2008), papaya (in the USA since 1999 and China since 2008), alfalfa (in the US initially in 2005–2007

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and then from 2011), squash (in the USA since 2004), apples (in the USA since 2016), potatoes (in the USA since 2015) and brinjal (in Bangladesh since 2015) have been planted.

The main traits so far commercialised convey:

- Tolerance to specific herbicides (notably to glyphosate and to glufosinate) in maize, cotton, canola (spring oilseed rape), soybean, sugar beet and alfalfa. This GM Herbicide Tolerant (GM HT) technology allows for the 'over the top' spraying of GM HT crops with these specific broad-spectrum herbicides, that target both grass and broad-leaved weeds but do not harm the crop itself;
- Resistance to specific insect pests of maize, cotton, soybeans and brinjal. This GM insect resistance (GM IR), or 'Bt' technology offers farmers resistance in the plants to major pests such as stem and stalk borers, earworms, cutworms and rootworm (eg, *Ostrinia nubilalis, Ostrinia furnacalis, Spodoptera frugiperda, Diatraea spp, Helicoverpa zea and Diabrotica spp*) in maize, bollworm/budworm (*Heliothis sp and Helicoverpa*) in cotton and caterpillars (*Helicoverpa armigeru)* in soybeans. Instead of applying insecticide for pest control, a very specific and safe insecticide is delivered via the plant itself through 'Bt' gene expression.

In addition, the GM papaya and squash referred to above are resistant to important viruses (eg, ringspot in papaya), the GM apples are non-browning and the GM potatoes (planted in 2016) have low asparagine (low acrylamide which is a potential carcinogen) and reduced bruising.

This paper presents an assessment of some of the key environmental impacts associated with the global adoption of these GM traits. The environmental impact analysis focuses on:

- *Changes in the amount of insecticides and herbicides applied to the GM crops relative to conventionally grown alternatives and;*
- *The contribution of GM crops towards reducing global Greenhouse Gas (GHG) emissions.*

  It is widely accepted that increases in atmospheric levels of greenhouse gases such as carbon dioxide, methane and nitrous oxide are detrimental to the global environment (see for example, Intergovernmental Panel on Climate Change 2006). Therefore, if the adoption of crop biotechnology contributes to a reduction in the level of greenhouse gas emissions from agriculture, this represents a positive development for the world.

The study integrates data for 2016 into the context of earlier developments and updates the findings of earlier analysis presented by the authors (eg, Brookes and Barfoot 2017).

The methodology and approach in this present discussion are unchanged to allow a direct comparison of the new with earlier data. Readers should however, note that some data presented in this paper are not directly comparable with data presented in previous analysis because the current paper takes into account new data (including revisions to data for earlier years). Also, in order to save readers the chore of consulting earlier papers for details of the methodology and arguments, these elements are included in full in this updated paper.

The aim has been to provide an up to date and as accurate as possible assessment of some of the key environmental impacts associated with the global adoption of GM crops. It is also hoped the analysis continues to make a contribution to greater understanding of the impact of this technology and facilitates more informed decision-making, especially in countries where crop biotechnology is currently not permitted.

RESULTS AND DISCUSSION

Results: environmental impacts of insecticide and herbicide use changes

HT Crops

A key impact of GM HT (largely tolerant to glyphosate) technology use has been a change in the profile of herbicides typically used. In general, a fairly broad range of, mostly selective (grass weed and broad-leaved weed) herbicides has been replaced by one or two broad-spectrum herbicides (mostly glyphosate) used in conjunction with one or a few other (complementary) herbicides (eg, 2 4,D). This has resulted in:

- Aggregate reductions in both the volume of herbicides used (in terms of weight of active ingredient applied) and the associated field EIQ values when compared to usage on conventional (non-GM) crops in some countries, indicating net improvements to the environment (for an explanation of the EIQ indicator, see the methodology section);
- In other countries, the average amount of herbicide active ingredient applied to GM HT crops represents a net increase relative to usage on the conventional crop alternative. However, even though the amount of active ingredient use has increased, in terms of the associated environmental impact, as measured by the EIQ indicator, the environmental profile of the GM HT crop has commonly been better than its conventional equivalent;
- Where GM HT crops (tolerant to glyphosate) have been widely grown, incidences of weed resistance to glyphosate have occurred (see additional discussion below) and have become a major problem in some regions (see www.weedscience.org). This can be attributed to how glyphosate was originally used with GM HT crops, where because of its highly effective, broad-spectrum post-emergence activity, it was often used as the sole method of weed control. This approach to weed control put tremendous selection pressure on weeds and as a result contributed to the evolution of weed populations dominated by resistant individuals. In addition, the facilitating role of GM HT technology in the adoption of RT/NT production techniques in North and South America has probably contributed to the emergence of weeds resistant to herbicides like glyphosate and to weed shifts towards those weed species that are not inherently well controlled by glyphosate. As a result, over the last 15 years, growers of GM HT crops have been (and are increasingly being advised to) using other herbicides (with different and complementary modes of action) in combination with glyphosate and in some cases adopting cultural practices (eg, revert to ploughing) in more integrated weed management systems. At the macro level, these changes have influenced the mix, total amount, cost and overall profile of herbicides applied to GM HT crops. This means that compared to the early 2000s, the amount and number of herbicide active ingredient used with GM HT crops in most regions has increased, and the associated environmental profile, as measured by the EIQ indicator, deteriorated. This increase in herbicide use is often cited by anti GM technology proponents (eg, Benbrook 2012) as an environmental failing of the technology. However, what such authors fail to acknowledge is that the amount of herbicide used on conventional crops has also increased over the same time period and that compared to the conventional alternative, the environmental profile of GM HT crop use has continued to represent an improvement compared to the conventional alternative (as measured by the EIQ indicator (Brookes and Barfoot 2017). It should also be noted that many of the herbicides used in conventional production systems had significant resistance issues themselves in the mid 1990s and this was one of the reasons why glyphosate tolerant soybean technology was rapidly adopted, as glyphosate provided good control of these weeds.

These points are further illustrated in the analysis below which examines changes in herbicide use by crop over the period 1996–2016 and specifically for the latest year examined, 2016.

GM HT Soybean

The environmental impact of herbicide use change associated with GM HT soybean adoption between 1996 and 2016 is summarised in Table 1. Overall, there has been a small net increase in the amount of herbicide active ingredient used (+ 0.4%), which equates to about 13

TABLE 1. GM HT soybean: summary of active ingredient usage and associated EIQ changes 1996–2016.

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
Romania (to 2006 only)	−0.02	−2.1	−10.5
Argentina	+10.8	+1.1	−8.8
Brazil	+28.1	+2.4	−6.6
US	−29.4	−2.7	−22.1
Canada	−3.34	−8.4	−23.8
Paraguay	+5.0	+6.1	−7.0
Uruguay	+0.81	+2.7	−7.4
South Africa	−0.63	−7.6	−22.9
Mexico	−0.002	−0.8	−3.7
Bolivia	+1.6	+6.0	−5.4
Aggregate impact: all countries	**+13.0**	**+0.4**	**−13.4**

Notes: Negative sign = reduction in usage or EIQ improvement. Positive sign = increase in usage or worse EIQ value

million kg more active ingredient applied to these crops than would otherwise have occurred if a conventional crop had been planted. However, the environmental impact, as measured by the EIQ indicator, improved by 13.4% due to the increased usage of more environmentally benign herbicides.

At the country level, some user countries recorded both a net reduction in the use of herbicide active ingredient and an improvement in the associated environmental impact, as measured by the EIQ indicator. Others, such as Brazil, Bolivia, Paraguay and Uruguay have seen net increases in the amount of herbicide active ingredient applied, though the overall environmental impact, as measured by the EIQ indicator has improved. The largest environmental gains have tended to be in developed countries where the usage of herbicides has traditionally been highest and where there has been a significant movement away from the use of several selective herbicides to one broad spectrum herbicide initially, and in the last few years, plus complementary herbicides, with different modes of action, targeted at weeds that are difficult to control with glyphosate.

In 2016, the amount of herbicide active ingredient applied to the global GM HT soybean crop increased by 2 million kg (+ 0.5%) relative to the amount reasonably expected if this crop area had been planted to conventional cultivars. This highlights the point above relating to recent increases in herbicide use with GM HT crops to take account of weed resistance issues. However, despite these increases in the volume of active ingredient used, in EIQ terms, the environmental impact of the 2016 GM HT soybean crop continued to represent an improvement relative to the conventional alternative (a 9% improvement).

GM HT Maize

The adoption of GM HT maize has resulted in a significant reduction in the volume of herbicide active ingredient usage (–239 million kg of active ingredient) and an improvement in the associated environmental impact, as measured by the EIQ indicator, between 1996 and 2016 (Table 2).

In 2016, the reduction in herbicide usage relative to the amount reasonably expected if this crop area had been planted to conventional cultivars was 11.8 million kg of active ingredient (–5.8%), with a larger environmental improvement, as measured by the EIQ indicator of 9%. As with GM HT soybeans, the greatest environmental gains have been in developed countries (eg, the

TABLE 2. GM HT maize: summary of active ingredient usage and associated EIQ changes 1996–2016.

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
US	–217.8	–10.0	–13.7
Canada	–9.7	–15.4	–19.8
Argentina	+1.0	+0.7	–5.3
South Africa	–2.3	–2.1	–6.9
Brazil	–8.1	+2.0	–8.2
Uruguay	+0.01	+2.6	–4.8
Vietnam	–1.0	–0.1	–0.7
Philippines	–2.5	–17.4	–35.0
Aggregate impact: all countries	**–239.3**	**–8.1**	**–12.5**

Notes: 1. Negative sign = reduction in usage or EIQ improvement. Positive sign = increase in usage or worse EIQ value.
2. Other countries using GM HT cotton – Brazil, Colombia and Mexico, not included due to lack of data

US and Canada), where the usage of herbicides has traditionally been highest.

GM HT Cotton

The use of GM HT cotton delivered a net reduction in herbicide active ingredient use of about 29.1 million kg over the 1996–2016 period (Table 3). This represents an 8.2% reduction in usage, and, in terms of the EIQ indicator, a 16.6% net environmental improvement. In 2016, the use of GM HT cotton technology cotton resulted in a 4 million kg reduction in herbicide active ingredient use (−16.2%) relative to the amount reasonably expected if this crop area had been planted to conventional cotton. In terms of the EIQ indicator, this represents a 16.7% environmental improvement.

Other HT Crops

GM HT canola (tolerant to glyphosate or glufosinate) has been grown in Canada, the US, and more recently Australia. GM HT sugar beet is grown in the US and Canada. The environmental impacts associated with changes in herbicide usage on these crops in the period 1996–2016 are summarised in Table 4. GM HT canola use has resulted in a significant reduction in the amount of herbicide active ingredient used relative to the amount reasonably expected if this crop area had been planted to conventional canola. Its use has also resulted in a net environmental improvement of 29.8%, as measured by the EIQ indicator.

In respect of GM HT sugar beet, the adoption of GM HT technology has resulted in a change

TABLE 3. GM HT cotton summary of active ingredient usage and associated EIQ changes 1996–2016.

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
US	–19.7	–6.3	–8.3
South Africa	+0.01	+2.3	–13.8
Australia	–4.2	–17.5	–23.1
Argentina	–5.2	–24.9	–30.1
Aggregate impact: all countries	**–29.1**	**–8.2**	**–10.7**

Notes: 1. Negative sign = reduction in usage or EIQ improvement. Positive sign = increase in usage or worse EIQ value
2. Other countries using GM HT cotton – Brazil, Colombia and Mexico, not included due to lack of data

TABLE 4. Other GM HT crops summary of active ingredient usage and associated EIQ changes 1996–2016.

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
GM HT canola			
US	–3.0	–29.6	–43.7
Canada	–23.6	–20.4	–32.8
Australia	–1.0	–3.9	–3.4
Aggregate impact: all countries	**–27.6**	**–18.3**	**–29.8**
2GM HT sugar beet			
US and Canada	–1.0	–10.0	–19.4

Notes: 1. Negative sign = reduction in usage or EIQ improvement. Positive sign = increase in usage or worse EIQ value
2. In Australia, one of the most popular type of production has been canola tolerant to the triazine group of herbicides (tolerance derived from non GM techniques). It is relative to this form of canola that the main farm income benefits of GM HT (to glyphosate) canola has occurred
3. InVigor' hybrid vigour canola (tolerant to the herbicide glufosinate) is higher yielding than conventional or other GM HT canola and derives this additional vigour from GM techniques
4. GM HT alfalfa is also grown in the US. The changes in herbicide use and associated environmental impacts from use of this technology is not included due to a lack of available data on herbicide use in alfalfa

in herbicide usage away from several applications of selective herbicides to fewer applications of, typically, a single herbicide (glyphosate). Over the period 2008–2016, the widespread use of GM HT technology in the US and Canadian sugar beet crops has resulted in a net reduction in the total volume of herbicides applied to the sugar beet crop relative to the amount reasonably expected if this crop area had been planted to conventional sugar beet (Table 4). The net impact on the environment, as measured by the EIQ indicator has been a 19% reduction in the EIQ value.

In 2016, the use of GM HT canola resulted in a 2.9 million kg reduction in the amount of herbicide active ingredient use (–22.6%) relative to the amount reasonably expected if this crop area had been planted to conventional canola. More significantly, there was an improvement in associated environmental impact, as measured by the EIQ indicator of 35%. The use of GM HT technology resulted in a decrease 82,000 kg of herbicide active ingredient being applied to the sugar beet crops in the US and Canada (–9%) relative to the amount reasonably expected if this crop area had been planted to conventional sugar beet. This also resulted in a net improvement in the associated environmental impact (–5%) as measured by the EIQ indicator.

Weed Resistance

As indicated above, weed resistance to glyphosate has become a major issue affecting some farmers using GM HT (tolerant to glyphosate) crops. Worldwide there are currently (accessed February 2018) 41 weeds species resistant to glyphosate of which many are not associated with glyphosate tolerant crops (Heap I International Survey of Herbicide Resistant Weeds -www.weedscience.org). This dataset shows that 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 addition, it shows that some of the first glyphosate resistant weeds developed in Australia in the mid 1990s before the adoption of GM HT crops and currently there are 16 weeds exhibiting resistance to glyphosate in Australia, even though the area using GM HT (tolerant to glyphosate) crops in the country is relatively small (about 1 million ha in 2016). In Argentina, Brazil and Canada, where GM HT crops are widely grown, the number of weed species exhibiting resistance to glyphosate are respectively 9, 8 and 5. Some 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 40%-60% of the total area annually devoted to maize, cotton and soybeans.

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 (I Heap, as above found at www.weedscience.org). This dataset also reports that herbicide resistant weeds pre-date the use of GM HT crops by decades and that there are, for example, 160 weed species that are resistant to ALS herbicides (eg, imazethapyr, cloransulam) and 74 weed species resistant to photosystem II inhibitor herbicides (eg, atrazine).

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. 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.

For example, in the 2016 US GM HT soybean crop, 89% of the GM HT soybean crop received an additional herbicide treatment of one of the following (four most used, after glyphosate) active ingredients 2,4-D (used pre-crop planting), chlorimuron, fomesafen and sulfentrazone (each used primarily after crop planting). This compares with 14% of the GM HT soybean crop receiving a treatment of one of the next 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) increased by 90% over this period. The increase in non-glyphosate herbicide use is primarily in response to public and private sector weed scientist recommendations to diversify weed management programmes and not to rely on a single herbicide mode of action for total weed management. It is interesting to note that in 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 that farmers continue to realise value in using glyphosate because of its broad-spectrum activity in addition to using other herbicides in line with integrated weed management advice.

On the small conventional crop, the average amount of herbicide active ingredient applied increased by 94% over the same period (marginally more than the rate of increase in use on the GM HT crop: 2006–2016) reflecting a shift in herbicides used rather than increased dose rates for some herbicides. The increase in the use of herbicides on the conventional soybean crop in the US can also be partly attributed to the on-going development of weed resistance to non-glyphosate herbicides commonly used and highlights that the development of weed resistance to herbicides is a problem faced by all farmers, regardless of production method. It is also interesting to note that since the mid 2000s, the average amount of herbicide active ingredient used on GM HT cotton in the US has increased through a combination of additional usage of glyphosate (about a 30% increase in usage per hectare) in conjunction with increasing use of other herbicides. All of the GM HT crop area planted to seed tolerant to glyphosate received treatments of glyphosate and at least one of the next five most used herbicides (trifluralin, acetochlor, 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). In other words, a quarter of the glyphosate tolerant crop used only glyphosate for weed control in 2006 compared to none of the crop relying solely on glyphosate in 2016. 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 glufosinate for 'over the top' treatments of GM HT cotton tolerant to both glyphosate and glufosinate (used on 32% of the GM HT cotton area in the US, compared to 10% of this area in 2012), as farmers rotate or alternate the primary herbicide used for weed control in these crops.

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).

GM IR Crops

The main way in which these technologies have impacted on the environment has been through reduced insecticide use between 1996 and 2016 (Table 5 and Table 6) with the GM IR technology effectively replacing insecticides used to control important crop pests. This is particularly evident in respect of cotton, which traditionally has been a crop on which intensive treatment regimes of insecticides were common place to control bollworm/budworm pests. In maize, the insecticide use savings have been more limited because the pests that the various technology targets tend to be less widespread in maize than budworm/bollworm pests are in cotton. In addition, insecticides were widely considered to have limited effectiveness against some pests in maize crops (eg, stalk borers) because the pests occur where sprays are not effective (eg, inside stalks). As a result of these factors, the proportion of the maize crop in most GM IR user countries that typically received insecticide treatments before the availability of GM IR technology was much lower than the share of the cotton crops receiving insecticide treatments (eg, in the US, no more than 10% of the maize crop typically received insecticide treatments targeted at stalk boring pests and about 30%-40% of the crop annually received treatments for rootworm).

The global insecticide savings from using GM IR maize and cotton in 2016 were, 8.7 million kg (–82% of insecticides typically targeted at maize stalk boring and rootworm pests) and 18.9 million kg (–56% of all insecticides used on cotton) respectively of active ingredient use relative to the amounts reasonably expected if these crop areas had been planted to conventional maize and cotton. In EIQ indictor terms, the respective environmental improvements in 2016 were 88% associated with insecticide use targeted at maize stalk boring and rootworm pests and 59% associated with cotton insecticides. Cumulatively since 1996, the gains

TABLE 5. GM IR maize: summary of active ingredient usage and associated EIQ changes 1996–2016.

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
US	–67.7	–50.2	–51.0
Canada	–0.75	–88.4	–62.4
Spain	–0.62	–36.6	–20.8
South Africa	–2.0	–70.0	–70.0
Brazil	–20.9	–90.1	–90.0
Colombia	–0.21	–69.2	–69.2
Vietnam	–0.01	–2.7	–2.7
Aggregate impact: all countries	**–92.1**	**–56.1**	**–58.6**

Notes: 1. Negative sign = reduction in usage or EIQ improvement. Positive sign = increase in usage or worse EIQ value
2. Other countries using GM IR maize – Argentina, Uruguay, Paraguay, Honduras and the Philippines, not included due to lack of data and/or little or no history of using insecticides to control these pests
3. % change in active ingredient usage and field EIQ values relates to insecticides typically used to target lepidopteran pests (and rootworm in the US and Canada) only. Some of these active ingredients are, however, sometimes used to control to other pests that the GM IR technology does not target

TABLE 6. GM IR cotton: summary of active ingredient usage and associated EIQ changes 1996–2016.

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
US	–22.5	–25.9	–19.6
China	–130.6	–30.9	–30.5
Australia	–19	–33.9	–35.3
India	–110.9	–30.4	–38.9
Mexico	–2.1	–13.9	–13.8
Argentina	–1.7	–24.2	–34.0
Brazil	–1.2	–12.7	–17.4
Aggregate impact: all countries	**–288.0**	**–29.9**	**–32.3**

Notes: 1. Negative sign = reduction in usage or EIQ improvement. Positive sign = increase in usage or worse EIQ value
2. Other countries using GM IR cotton –Colombia, Burkina Faso, Paraguay, Pakistan and Myanmar not included due to lack of data
3. % change in active ingredient usage and field EIQ values relates to all insecticides (as bollworm/budworm pests are the main category of cotton pests worldwide). Some of these active ingredients are, however, sometimes used to control to other pests that that the GM IR technology does not target

have been a 92.1 million kg reduction in maize insecticide active ingredient use and a 288 million kg reduction in cotton insecticide active ingredient use (Table 5 and Table 6).

In 2016, IR soybeans were in their fourth year of commercial use in South America (mostly Brazil). During this period (2013–2016), the insecticide use (active ingredient) saving relative to the amount reasonably expected if this crop area had been planted to conventional soybeans was 7.4 million kg (6% of total soybean insecticide use), with an associated environmental benefit, as measured by the EIQ indicator saving of 6.3%.

Aggregated (Global Level) Impacts

At the global level, GM technology has contributed to a significant reduction in the negative environmental impact associated with insecticide and herbicide use on the areas devoted to GM crops. Since 1996, the use of pesticides on the GM crop area has fallen by 671.4 million kg of active ingredient (an 8.2% reduction) relative to the amount reasonably expected if this crop area had been planted to conventional crops. The environmental impact associated with herbicide and insecticide use on these crops, as measured by the EIQ indicator, improved by 18.4%. In 2016, the environmental benefit was equal to a reduction of 48.5 million kg of pesticide active ingredient use (–8.1%), with the environmental impact associated with insecticide and herbicide use on these crops, as measured by the EIQ indicator, improving by 18.3%.

At the country level, US farms have seen the largest environmental benefits, with a 361 million kg reduction in pesticide active ingredient use (54% of the total). This is not surprising given that US farmers were first to make widespread use of GM crop technology, and for several years, the GM adoption levels in all four US crops have been in excess of 80%, 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 241 million kg (1996–2016).

Results: greenhouse Gas Emission Savings

Reduced Fuel Use

The fuel savings associated with making fewer spray runs in GM IR crops of maize and cotton (relative to conventional crops) and the switch from Conventional Tillage (CT) to Reduced Tillage or No Tillage (RT/NT) farming systems facilitated by GM HT crops, have resulted in permanent savings in carbon dioxide emissions. In 2016, this amounted to a saving of 2,945 million kg of carbon dioxide, arising from reduced fuel use of 1,309 million litres (Table 7). These savings are equivalent to taking 1.8 million cars off the road for one year.

The largest fuel use-related reductions in carbon dioxide emissions have come from the adoption of GM HT technology in soybeans and how it has facilitated a switch to RT/NT production systems with their reduced soil cultivation practices (67% of total savings 1996–2016). These savings have been greatest in South America.

Over the period 1996 to 2016, the cumulative permanent reduction in fuel use has been about 29,169 million kg of carbon dioxide, arising from reduced fuel use of 10,925 million litres. In terms of car equivalents, this is equal to taking 18 million cars off the road for a year.

Additional Soil Carbon Storage/Sequestration

As indicated earlier, the widespread adoption and maintenance of RT/NT production systems in North and South America, facilitated by GM HT crops (especially in soybeans) has improved growers' ability to control competing weeds, reducing the need to rely on soil cultivation and seed-bed preparation as means to getting good levels of weed control. As a result, as well as tractor fuel use for tillage being reduced, soil quality has been enhanced and levels of soil erosion cut. In turn, more carbon remains in the soil and this leads to lower GHG emissions.

Based on savings arising from the rapid adoption of RT/NT farming systems in North and South America, we estimate that an extra 6,586 million kg of soil carbon has been sequestered in 2016 (equivalent to 24,172 million kg of carbon dioxide that has not been released into the global atmosphere). These savings are equivalent to taking 14.9 million cars off the road for one year (Table 8).

The additional amount of soil carbon sequestered since 1996 has been equivalent to 251,390 million tonnes of carbon dioxide that has not been released into the global atmosphere. Readers should note that these estimates are based on fairly conservative assumptions and therefore the true values

TABLE 7. Carbon storage/sequestration from reduced fuel use with GM crops 2016.

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)
US: GM HT soybean	202	533	329
Canada: GM HT soybeans	18	47	29
Argentina: GM HT soybean	265	709	440
Brazil GM HR soybean	191	509	314
Bolivia, Paraguay, Uruguay: GM HT soybean	66	175	108
US: GM HT maize	156	416	257
Canada: GM HT maize	7	19	12
Canada: GM HT canola	72	192	118
Global GM IR cotton	16	42	26
Brazil IR maize	37	100	62
Us/Canada/Spain/South Africa: IR maize	5	12	7
South America: IR soybeans	71	190	117
Total	***1,106***	***2,945***	***1,819***

Notes: 1. Assumption: an average family car in 2017 produces 129 grams of carbon dioxide per km. A car does an average of 12,553 km/year and therefore produces 1,619 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

TABLE 8. Context of carbon sequestration impact 2016: 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)
US: GM HT soybean	782	2,871	1,773
Canada: GM HT soybeans	68	249	154
Argentina: GM HT soybean	1,958	7,187	4,438
Brazil GM HR soybean	1,407	5,163	3,188
Bolivia, Paraguay, Uruguay: GM HT soybean	484	1,776	1,097
US: GM HT maize	1,608	5,903	3,645
Canada: GM HT maize	15	54	33
Canada: GM HT canola	264	968	598
Global GM IR cotton	0	0	0
Brazil IR maize	0	0	0
Us/Canada/Spain/South Africa: IR maize	0	0	0
South America: IR soybeans (included in HT soybeans above)	0	0	0
Total	***6,586***	***24,171***	***14,926***

could be higher. Also, some of the additional soil carbon sequestration gains from RT/NT systems may be lost if subsequent ploughing of the land occurs.

Estimating the possible losses that may arise from subsequent ploughing would be complex and difficult to undertake. This factor should be taken into account when using the estimates presented in this paper. It should also be noted that this soil carbon saving is 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.

Cumulatively, the amount of carbon sequestered may be higher than these estimates due to year-on-year benefits to soil quality (eg, less soil erosion, greater water retention and reduced levels of nutrient run off). However, it is equally likely that the total cumulative soil sequestration gains have been lower because only a proportion of the crop area will have remained in NT/RT.

It is, nevertheless, not possible to confidently estimate cumulative soil sequestration gains that take into account reversions to conventional tillage because of a lack of data. Consequently, the estimate provided of 251,390 million kg of carbon dioxide not released into the atmosphere should be treated with caution.

Aggregating the carbon sequestration benefits from reduced fuel use and additional soil carbon storage, the total carbon dioxide savings in 2016 are equal to about 27,117 million kg, equivalent to taking 16.75 million cars off the road for a year. This is equal to 54% of registered cars in the UK.

CONCLUSIONS

Crop biotechnology has been used by many farmers around the world for more than twenty years and currently more than 18 million farmers a year plant seeds containing this technology. This seed technology has helped farmers be more efficient with their application of crop protection products, which not only reduces their environmental impact, but saves time and money. The technology is also changing agriculture's carbon footprint, helping farmers adopt more sustainable practices such as reduced tillage, which has decreased the burning of fossil fuels and allowed more carbon to be retained in the soil. This has led to a decrease in carbon emissions. In relation to GM HT crops, however, over reliance on the use of glyphosate by farmers, in some regions, has contributed to the development of weed resistance. As a result, farmers have, over the last 15 years, adopted more integrated weed management strategies incorporating a mix of herbicides and non-herbicide-based weed control practices. This means that the magnitude of the original environmental gains associated with changes in herbicide use with GM HT crops have diminished. Despite this, the adoption of GM HT crop technology in 2016 continues to deliver a net environmental gain relative to the conventional alternative and, together with GM IR technology, continues to provide substantial net environmental benefits. These findings are also consistent with analysis by other authors (Fernando-Cornejo et al. 2014; Klumper and Qaim 2014).

METHODOLOGY

This analysis draws on a combination of existing literature and analysis by the authors of crop and country-specific farm level changes in husbandry practices and pesticide usage data. In particular, the analysis of pesticide usage changes with GM crops takes into consideration how farmers have made changes to weed control practices so as address weed resistance development to the main herbicide (glyphosate) used with GM HT crops.

Methodology: environmental Impacts from Insecticide and Herbicide Use Changes

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

Comparison data ideally derives from farm level surveys which collect usage data on the different forms of production. A search of the literature on insecticide or herbicide use change with GM crops shows that the number of studies exploring these issues is limited (eg, Qaim and Janvry 2005, Qaim and Traxler, 2005, Pray et al. 2002) with even fewer (eg, Brookes 2005, 2008), providing data to the pesticide (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 and, the only country in which pesticide usage data is collected (by private market research companies) on an annual basis, and which allows a comparison between GM and conventional crops to be made, is the US. The US Department of Agriculture (USDA) conducts pesticide usage surveys but these are not conducted on an annual basis for each crop (eg, the last time maize was included was 2016 and previous to this, in 2014, 2010 and 2005, for soybeans the last time included was 2015 and before that, 2012) and do not disaggregate usage by production type (GM versus conventional).

Even where national pesticide use survey data is available, it can be of limited value. Quantifying herbicide or insecticide usage changes with GM crop technology adoption requires an assessment of, not only what is currently used with GM crops, but also what herbicides/insecticides might reasonably be expected to be used in the absence of crop biotechnology on the relevant crops (ie, if the entire crops used non-GM production methods). Applying usage rates for the current (remaining) conventional crops is one approach, however, this invariably under estimates what usage might reasonably be in the absence of crop biotechnology, because the conventional cropping dataset used relates to a relatively small, unrepresentative share of total crop area. This has been the case, for example, in respect of the

US maize, canola, cotton and soybean crops for many years. Thus in 2016, the conventional share (not using GM HT technology) of each crop was only 6%, 8%, 7% and 5% respectively for soybean, maize, cotton and canola, with the conventional share having been below 50% of the total since 1999 in respect of the soybean crop, since 2001 for the cotton and canola crops, and since 2007 for the maize crop (source: USDA NASS 2017).

The reasons why herbicide/insecticide usage levels from this small conventional crop dataset is unrepresentative of what might reasonably be expected if all of the current area growing GM crops reverted to conventional seed types are:

- Although pest/weed problems/damage vary by year, region and within region, farmers' who consistently farm conventionally may be those with relatively low levels of pest/weed problems, and hence see little, if any economic benefit from using the GM traits targeted at 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 non-adopting farmers tend to be below the levels that would reasonably be expected on an average farm with more typical pest/weed infestations and where farmers are more wiling to adopt new technology;
- Some of the farms continuing to use conventional seed use extensive, low intensity production methods (including organic) which feature, limited (below average) use of herbicides/insecticides. The usage patterns of this sub-set of growers is therefore likely to understate usage for the majority of farmers if they all returned to farming without the use of GM technology;
- The widespread adoption of GM IR technology has resulted in 'area-wide' suppression of target pests in maize and cotton 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).
- Some 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 use higher levels of insecticide/herbicide than they did in the pre-GM crop days. Nevertheless, the decision to use more pesticide or not would be made according to individual assessment of the potential benefits (eg, from higher yields) compared to the cost of additional pesticide use.

The poor representativeness of the small conventional dataset has been addressed by firstly, using the average recorded values for insecticide/herbicide usage on conventional crops for years only when the conventional crop accounted for the majority 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 crop was no longer using crop biotechnology, based on opinion from extension and industry advisors across the country as to what farmers might reasonably be expected to do for pest and weed control practices, including typical insecticide/herbicide application rates. Lastly, these 'extension service' identified application rates were cross checked (and subject to adjustment) with recorded usage levels of key herbicide and insecticide active ingredients from pesticide usage surveys (where available) so as to minimise the chance of usage levels for the conventional alternative being overstated. Overall, this approach has been applied in a number of countries where pesticide usage data is available, though in some, because of the paucity of available data, the analysis relies more on extension/advisor opinion and knowledge of actual and potential pesticide use.

This methodology has been used by others (Sankula and Blumenthal 2003, 2006, Johnson and Strom 2007). It also has the advantage of providing comparisons of current crop protection practices on both GM crops and the conventional alternatives and so takes into account dynamic changes in crop protection and weed control management practices and technologies (eg, to address weed resistance development) rather than making comparisons solely on past practices. Details of how this methodology has been applied to the 2016 calculations, sources used for each trait/country combination examined and examples of typical conventional versus GM pesticide applications are provided in Appendix 1 and 2.

The environmental impact associated with pesticide use changes with GM crops has most commonly been presented in the literature in terms of the volume (quantity) of pesticide applied. This is, however, not a good measure of environmental impact because the toxicity of each pesticide is not directly related to the amount (weight) applied. There exist alternative (and better) measures that have been used by a number of authors of peer reviewed papers to assess the environmental impact of pesticide use change with GM crops. In particular, there are a number of peer reviewed papers that utilise the Environmental Impact Quotient (EIQ) developed at Cornell University by Kovach et al. 1992 and updated annually (eg, Brimner et al. 2005, Kleiter 2005, Biden et al. 2018). This effectively integrates the various environmental impacts of individual pesticides into a single 'field value per hectare'. The EIQ value is multiplied by the amount of pesticide active ingredient (ai) used per hectare to produce a field EIQ value. For example, the EIQ rating for glyphosate is 15.33. By using this rating multiplied by the amount of glyphosate used per hectare (eg, a hypothetical example of 1.1 kg applied per ha), the field EIQ value for glyphosate would be equivalent to 16.86/ha. The EIQ indicator used is therefore a comparison of the field EIQ/ha for conventional versus GM crop production systems, with the total environmental impact or load of each system, a direct function of respective field EIQ/ha values and the area planted to each type of production (GM versus conventional). The EIQ indicator provides an improved assessment of the impact of GM crops on the environment when compared to only examining changes in volume of active ingredient applied, because it draws on some of the key toxicity and environmental exposure data related to individual products, as applicable to impacts on farm workers, consumers and ecology.

The authors of this analysis have also used the EIQ indicator now for several years because it:

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

The authors, do, however acknowledge that the EIQ is only a hazard indicator and has important weaknesses (see for example, Peterson and Schleier 2014 and Kniss and Coburn 2015). It is a hazard rating indicator that does not assess risk or probability of exposure to pesticides. It also relies on qualitative assumptions for the scaling and weighting of (quantitative) risk information that can result, for example, in a low risk rating for one factor (eg, impact on farm workers) may cancel out a high risk rating factor for another factor (eg, impact on ecology). Fundamentally, assessing the full environmental impact of pesticide use changes with different production systems is complex and requires an evaluation of risk exposure to pesticides at a site-specific level. This requires substantial collection of (site-specific) data (eg, on ground water levels, soil structure) and/or the application of standard scenario models for exposure in a number of locations. Undertaking such an exercise at a global level would require a substantial and ongoing input of labour and time, if comprehensive environmental impact of pesticide change analysis is to be completed. It is not surprising that no such exercise has, to date been undertaken, or likely to be in the near future.

Despite the acknowledged weaknesses of the EIQ as an indictor of pesticide environmental impact, the authors of this paper continue to use it because it is, in our view, a superior indicator to only using amount of pesticide active ingredient applied. In this paper, the EIQ indicator is used in conjunction with examining changes in the volume of pesticide active ingredient applied.

Detailed examples of the relevant amounts of active ingredient used and their associated field EIQ values for GM versus conventional crops for the year 2016 are presented in Appendix 2.

Methodology: impact of Greenhouse Gas Emissions

Assessment of the impact of GM crop use on greenhouse gas emissions combines reviews of literature relating to fuel use and tillage systems, coupled with evidence of how GM crop usage has impacted on fuel use and tillage systems. Reductions in the level of GHG emissions associated with the adoption of GM crops are acknowledged in a wide body of literature (Conservation Tillage and Plant Biotechnology (CTIC) 2002, American Soybean Association Conservation Tillage Study 2001, Fabrizzi et al. 2003, Jasa 2002, Reicosky 1995, Robertson et al. 2000, Johnson et al. 2005, Derpsch et al. 2010, Eagle et al. 2012, Olson et al. 2013).

First, GM crops contribute to a reduction in fuel use from less frequent herbicide or insecticide applications and a reduction in the energy use in soil cultivation. For both herbicide and insecticide applications, the quantity of energy required to apply the pesticides depends upon the application method. For example, in the US, a typical method of application is with a 50-foot boom sprayer which consumes approximately 0.84 litres/ha (Lazarus 2018). In terms of GHG, each litre of tractor diesel consumed contributes an estimated 2.67 kg of carbon dioxide into the atmosphere (so one less application reduces carbon dioxide emissions by 2.24 kg/ha). Given that many farmers apply insecticides via sprayers pulled by tractors, which use higher levels of fuel than self-propelled boom sprayers, these estimates for reductions in carbon emissions, which are based on self-propelled boom application, probably understate the carbon benefits.

In addition, there has been a shift from CT to RT/NT. No-till farming means that the ground is not ploughed at all, while reduced tillage means that the ground is disturbed less than it would be with traditional tillage systems. For example, under a no-till farming system, soybean seeds are planted through the organic material that is left over from a previous crop such as corn, cotton or wheat) facilitated by GM HT technology (see for example, CTIC 2002 and American Soybean Association 2001, especially where soybean growing and/or a soybean: corn rotation are commonplace. Before the introduction of GM HT technology, RT/NT systems were practised by some farmers with varying degrees of success using a number of herbicides, though in many cases, a reversion to CT was common after a few years due to poor levels of weed control. The availability of GM HT technology provided growers with an opportunity to control weeds in a RT/NT system with a non-residual, broad-spectrum, foliar herbicide as a 'burndown' pre-seeding treatment followed by a post-emergent treatment when the crop became established, in what proved to be a more reliable and commercially attractive system than was previously possible. 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 50% increase in the RT/NT soybean area in the US and a seven-fold increase in Argentina since 1996. In 2016, RT/NT production accounted for 83% and 89% respectively of total soybean production in the US and Argentina, with over 95% of the RT/NT soybean crop area in both countries using GM HT technology.

Substantial growth in RT/NT production systems have also occurred in Canada, where the proportion of the total canola crop accounted for by RT/NT systems increased from 25% in 1996 to 50% by 2004, and in 2016, accounted for 75% of the total crop was planted to GM HT cultivars (80% the GM HT crop was RT/NT).

This shift away from a plough-based, to a RT/NT production system has resulted in a reduction in fuel use. The fuel savings used in this paper are drawn from a review of literature including Jasa 2002, CTIC 2002, University of Illinois 2006, USDA Energy Estimator 2013, Reeder 2010 and the USDA Comet-VR model 2014. In this analysis, it is assumed that the adoption of NT farming systems in soybean production reduces cultivation and seedbed preparation fuel usage by 27.12 litres/ha compared with traditional conventional tillage and in the case of RT (mulch till) cultivation by 10.39 litres/ha. In the case of maize, NT results in a saving of 24.41 litres/ha and 7.52 litres/ha in the case of RT compared with conventional intensive tillage. These are conservative estimates and are in line with the USDA Energy Estimator for soybeans and maize.

The adoption of NT and RT systems in respect of fuel use therefore results in reductions of carbon dioxide emissions of 72.41 kg/ha and 27.74 kg/ha respectively for soybeans and 65.17 kg/ha and 20.08 kg/ha for maize.

Secondly, the use of RT/NT farming systems increases the amount of organic carbon in the form of crop residue that is stored or sequestered in the soil and therefore reduces carbon dioxide emissions to the environment (Angers and Eriksen-Hamel 2008, Calegari et al. 2000, Robertson et al. 2000, Lal 2004, Bernacchi et al. 2005, Lal 2005, Johnson et al. 2005, Leibeig et al. 2005, Intergovernmental Panel on Climate Change 2006, Wutzler and Reichstein 2006, Baker et al. 2007, Blanco-Canqui and Lal 2008, Lal. 2010, Michigan State University 2016). This literature shows that carbon sequestered levels vary by soil type, cropping system, eco-region and tillage depth and that tillage systems affect levels of other GHG emissions such as methane and nitrous oxide, as well as crop yield.

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 benefits described in the literature can be realised. However, if the NT crop area is returned to a conventional tillage system, a proportion of the soil organic carbon gain will be lost. The temporary nature of this form of carbon storage only becomes permanent when farmers adopt a continuous NT system, which as indicated earlier, is highly dependent upon having an effective herbicide-based weed control system.

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 15–20 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).

Drawing on the literature and models referred to above, the analysis presented in the following sub-sections assumes the following:

US: The soil carbon sequestered by tillage system for corn in continuous rotation with soybeans is assumed to be a net sink of 250 kg of carbon/ha/year based on:

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

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

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

Argentina and Brazil: 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 editions of this report the difference used was 300 kg carbon/ha/year.

Overall, the GHG emission savings derived from reductions in fuel use for crop spraying have been applied only to the area of GM IR crops worldwide (but excluding countries where conventional spraying has traditionally been by hand, such as in India and China) and the savings associated with reductions in fuel from less soil cultivation plus soil carbon storage have been limited to NT/RT areas in North and South America that have utilised GM HT technology. Lastly, some RT/NT areas have also been excluded where the consensus view is that GM HT technology has not been the primary reason for use of these non plough-based systems (eg, parts of Brazil).

Additional detail relating to the estimates for carbon dioxide savings at the country and trait levels are presented in Appendix 3.

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APPENDIX 1. DETAILS OF METHODOLOGY AS APPLIED TO 2016 CALCULATIONS OF ENVIRONMENTAL IMPACT ASSOCIATED WITH PESTICIDE USE CHANGES

GM IR maize (targeting stalk boring pests) 2016

Country	Area of trait ('000 ha)	Maximum area treated for stalk boring pests: pre-GM IR ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units (millions)
US	27,734	3,511	0.23	0.58	12.8	22.8	–1,229	–35.1
Canada	1,048	66	0.04	0.64	4.8	24.8	–39	–1.0
Argentina	4,009	0	0	0	0	0	0	0
Philippines	653	Very low – assumed zero	0	0	0	0	0	0
South Africa	2,392	1,768	0	0.08	0	3.8	–165	–6.0
Spain	129	35	0.36	1.32	0.9	26.9	–34.3	–0.92
Uruguay	46	Assumed to be zero: as Argentina	0	0	0	0	0	0
Brazil	14,881	8,443	0 targeted at stalk boring pests	0.36 targeted at stalk boring pests	0 targeting stalk boring pests	21.5	–3,006	–181
Colombia	80	46	0 targeted at stalk boring pests	0.56 targeted at stalk boring pests	0 targeting stalk boring pests	15.9	–25	–0.72
Vietnam	35	770	0 targeted at stalk boring pests	0.34 targeted at stalk boring pests	0 targeted at stalk boring pests	9.51	11.9	0.33

Notes:
1. Other countries: Honduras, Paraguay and EU countries: not examined due to lack of data (Honduras and Paraguay) or very small area planted (EU countries other than Spain)
2. Baseline amount of insecticide active ingredient shown in Canada refers only to insecticides used primarily to control stalk boring pests

GM IR maize (targeting rootworm) 2016

Country	Area of trait ('000 ha)	Maximum area treated for rootworm pests: pre GM IR ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units (millions)
US	16,645	10,391	0.2	0.6	12	32.5	–4,158	–213.1

Note:
1. There are no Canadian-specific data available: analysis has therefore not been included for the Canadian crop of 695,000 ha planted to seed containing GM IR traits targeted at rootworm pests
2. The maximum area treated for corn rootworm (on which the insecticide use change is based) is based on the historic area treated with insecticides targeted at the corn rootworm. This is 30% of the total crop area. The 2016 maximum area on which this calculation is made has been reduced by 138,000 ha to reflect the increased use of soil-based insecticides (relative to usage in a baseline period of 2008–2010) that target the corn rootworm on the GM IR (targeting corn rootworm) area. It is assumed this increase in usage is in response to farmer concerns about the possible development of CRW resistance to the GM IR rootworm technology that has been reported in a small area in the US

GM IR cotton 2016

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units (millions)
US	3,232	0.85	1.78	27.68	47.46	–3,010	–63.9
China	2,755	1.57	2.74	73.0	103.4	–3,223	–83.7
Australia	551	0.91	2.1	25.0	65.0	–656	–22.1
Mexico	94	3.60	5.22	120.4	177.0	–152	–5.3
Argentina	240	0.7	2.42	19.9	76.7	–78	–5.5
India	11,416	0.53	1.67	14.78	72.4	–11,648	–595.3
Brazil	511	0.41	0.736	15.1	38.2	–167	–11.8

Notes:
1. Due to the widespread and regular nature of bollworm and budworm pest problems in cotton crops, GM IR areas planted are assumed to be equal to the area traditionally receiving some form of conventional insecticide treatment
2. South Africa, Burkina Faso, Columbia, Pakistan and Myanmar not included in analysis due to lack of data on insecticide use changes
3. Brazil: due to a lack of data, usage patterns from Argentina have been assumed

GM HT soybean 2016

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units (millions)
US	31,473	2.512	2.409	43.59	45.20	–3,238	–50.5
Canada	1,918	1.52	1.79	23.30	33.71	–518	–19.7
Argentina	18,501	3.59	3.58	54.53	61.21	+ 502	–123.6
Brazil	32,700	2.59	2.53	40.6	47.4	+ 1,886	–188.4
Paraguay	3,168	3.57	3.3	44.43	51.84	+ 859	–23.5
South Africa	545	1.68	1.95	28.73	42.51	–146	–7.5
Uruguay	1,060	3.01	3.0	46.23	52.91	+ 29	–7.1
Bolivia	1,028	3.18	3.03	50.6	51.8	+ 279	–7.6
Mexico	3	1.62	1.76	24.8	41.0	–0.4	–0.04

Notes: Due to lack of country-specific data, usage patterns in Paraguay assumed for Bolivia. Industry sources confirm this assumption reasonably reflects typical usage

GM IR (Intacta) soybeans 2016

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units (millions)
Brazil	17,294	1.43	1.6	30.65	47.9	–2,983	–639.8
Paraguay	1,485	1.43	1.6	30.65	47.9	–119	–11.1
Argentina	3,162	0.23	0.31	7.74	9.0	–253	–24.1
Uruguay	359	0.23	0.31	7.74	9.0	–29	–3.5

GM HT maize 2016

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units (millions)
US	31,245	3.17	3.60	60.19	70.32	−13,401	−316.5
Canada			glyphosate tolerant	1,272	1.83	2.71	37.0
61.1	−243	−18.1					
Canada			glufosinate tolerant	13	1.64	2.71	36.0
61.0	−13	−0.3					
Argentina	4,193	3.99	3.53	71.8	73.6	+ 1,945	−7.6
South Africa	1,928	2.33	2.22	39.46	46.45	+ 212	−13.5
Brazil	11,908	2.81	2.81	48.86	56.45	No change	−90
Uruguay	49	3.99	3.53	71.8	73.6	+ 23	−0.1
Philippines	655	1.44	1.90	22.08	43.41	−301	−14
Vietnam	35	0.984	1.01	15.08	20.55	−0.9	−0.19

Notes:
1. Colombia: not included due to lack of data on weed control methods and herbicide product use
2. Uruguay – based on Argentine data – industry sources confirm herbicide use in Uruguay is very similar

GM HT cotton 2016

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units (millions)
US	3,424	4.30	5.07	80.06	92.62	−2,620	−43.0
S Africa	18	1.80	1.81	27.6	31.9	−0.2	−0.08
Australia	568	5.26	7.47	90.22	143.4	−1,253	−30.2
Argentina	240	4.06	4.72	64.0	78.4	−158	−3.5

Notes:
1. Mexico and Colombia: not included due to lack of data on herbicide use

GM HT canola 2016

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units (millions)
US glyphosate tolerant	295	1.24	1.1	18.55	23.22	+ 42	−1.38
US glufosinate tolerant	319	0.424	1.1	8.57	23.22	−214	−4.68
Canada glyphosate tolerant	3,264	1.24	1.1	18.55	23.22	+ 469	−15.2
Canada glufosinate tolerant	4,417	0.424	1.1	8.57	23.22	−2,968	−64.7
Australia glyphosate tolerant	448	0.94	1.46	15.03	22.31	−235	−3.3

GM herbicide tolerant sugar beet 2016

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/HA GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units
US	456	2.86	3.04	46.25	48.92	–82	–1.2

APPENDIX 2. EXAMPLES OF EIQ CALCULATIONS

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 2016

	Active ingredient (kg/ha)	Field EIQ/ha value
GM HT soybean	3.59	54.53
Source: Kleffmann dataset on pesticide use 2015/16		
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	**3.58**	**61.21**

Sources: AAPRESID, Kleffmann Global, Monsanto Argentina

Typical insecticide regimes for cotton in India 2016

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**
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**
Weighted average GM IR cotton	**0.53**	**14.78**

Source: Monsanto India, AMIS Global

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

Data sources (for pesticide usage data)

	Sources of data for assumptions
US	Gianessi and Carpenter (1999) Sankala & Blumenthal (2003 & 2006) Johnson S & Strom S (2007) Own analysis (2010–2016) All of the above mainly for conventional regimes (based on surveys and consultations of extension advisors and industry experts) Kynetec – private market research data on pesticide usage. Is the most comprehensive dataset on crop pesticide usage at the farm level and allows for disaggregation to cover biotech versus conventional crops. This source primarily used for usage on GM traits
Argentina	AMIS Global & Kleffmann - private market research data on pesticide use. Is the most detailed dataset on crop pesticide use AAPRESID (no till farmers association) – personal communications 2007 Monsanto Argentina (personal communications 2005, 2007, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017) Qaim M & De Janvry A (2005) Qaim M & Traxler G (2005)
Brazil	AMIS Global & Kleffmann - private market research data on crop pesticide use. Is the most detailed dataset on crop pesticide use Monsanto Brazil (2008) Galveo A (2009 and 2012), plus personal communications Monsanto Brazil (personal communications 2007, 2009, 2011, 2013, 2014, 2015, 2016)
Uruguay	Kleffmann and as Argentina for conventional
Paraguay	As Argentina for conventional soybeans (over the top usage), Kleffmann for GM HT soybean
Bolivia	As Paraguay: no country-specific data identified
Canada	George Morris Center (2004) Canola Council (2001) Smyth S et al (2011) Weed Control Guide Ontario (updated annually)[6]
S Africa	Monsanto S Africa (personal communications 2005, 2007, 2009, 2010, 2011, 2012, 2014, 2015, 2016) Ismael Y et al (2002) Kleffmann
Romania	Kleffmann, Brookes (2005)
Australia	Kleffmann Doyle et al (2003) CSIRO (2005) Monsanto Australia (personal communications 2005, 2007, 2009, 2010, 2011,2012, 2014, 2015, 2016) Fisher J & Tozer P (2009)
Spain	Brookes (2008)
China	Kleffmann Pray et al. (2002) Monsanto China personal communication (2007, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016)
Mexico	Monsanto Mexico (2005, 2007, 2008, 2009, 2013, 2016, 2017) Traxler G et al (2001)
India	Kleffmann, Kynetec APCOAB (2006) IMRB (2006,2007) Monsanto India (2007, 2008, 2009, 2010, 2011, 2013, 2016, 2017) – personal communications
Vietnam	Kynetec, Brookes (2017)
Philippines	Kynetec, Monsanto Philippines personal communication and survey of GM HT growers (2017 unpublished)

APPENDIX 3. CARBON SAVING ESTIMATES: ADDITIONAL INFORMATION

US soybeans: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1996–2016)

	Annual reduction based on 1996 average (litres/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1996	0.00	25.98	0.00	0.00
1997	0.40	28.33	11.36	30.33
2000	0.92	30.15	27.66	73.86
2010	4.11	31.56	129.58	345.99
2015	5.97	33.12	197.63	527.67
2016	5.97	33.48	199.77	533.39
Total			**2,009.31**	**5,364.84**

Assumption: baseline fuel usage is the 1996 level of 36.6 litres/ha
Note: Due to rounding the cumulative totals may not exactly sum the annual totals. This applies to all tables in this appendix

US soybean: potential additional soil carbon sequestration (1996 to 2016)

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total additional carbon sequestered (million kg)	Total additional Carbon dioxide sequestered (million kg)
1996	0.0	26.0	0.00	0.00
1997	1.4	28.3	39.33	144.35
2000	3.3	30.1	100.23	367.85
2010	15.7	31.6	495.86	1,819.80
2015	23.4	33.1	773.82	2,839.91
2016	23.4	33.5	782.20	2,870.68
Total			**7,715.26**	**28,315.10**

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

Argentine soybean: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1996–2016)

	Annual reduction based on 1996 average of 39.1 (litres/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1996	0.0	5.9	0.0	0.00
1997	2.3	6.4	14.7	39.16
2000	3.0	10.6	31.6	84.45
2010	13.7	18.2	249.8	667.06
2015	14.3	19.4	277.0	739.49
2016	14.3	18.6	265.5	708.90
Total			**3,482.2**	**9,300.14**

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

Argentine soybean: potential additional soil carbon sequestration (1996 to 2016)

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total additional carbon sequestered (million kg)	Total additional Carbon dioxide sequestered (million kg)
1996	0.0	5.91	0.0	0.0
1997	16.92	6.39	108.17	396.98
2000	22.03	10.59	233.27	856.09
2005	79.08	15.20	1,202.00	4,411.35
2015	105.28	19.40	2,042.51	7,496.01
2016	105.28	18.60	1,958.28	7,186.90
Total			**25,687.30**	**94,272.39**

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

Brazil (3 southernmost states) soybean: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1997–2016)

	Annual reduction based on 1997 average of 40.9 (litres/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1997	0.00	6.19	0.00	0.00
1998	1.36	6.12	8.30	22.15
2000	4.07	5.98	24.34	65.00
2010	14.92	9.13	136.24	363.75
2015	16.27	11.54	187.77	501.35
2016	16.27	11.72	190.77	509.35
Total			**1,969.60**	**5,258.81**

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

Brazil (3 southernmost states) soybean: potential additional soil carbon sequestration (1997 to 2016)

	Annual increase in carbon sequestered based on 1997 average (kg carbon/ha)	Crop area (million ha)	Total addition carbon sequestered (million kg)	Total addition Carbon dioxide sequestered (million kg)
1997	0.0	6.2	0.00	0.00
1998	10.0	6.1	61.19	224.57
2000	30.0	6.0	179.52	658.84
2010	110.0	9.1	1,004.69	3,687.19
2015	120.0	11.5	1,384.75	5,082.04
2016	120.0	11.7	1,406.83	5,163.07
Total			**14,524.96**	**53,306.63**

Assumption: NT/RT = + 175 kg carbon/ha/yr, CT = –25 kg carbon/ha/yr

US maize: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1998–2016)

	Annual reduction based on 1997 average (litres/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1997	0.00	32.19	0.00	0.00
1998	–0.30	32.44	–9.58	–25.57
2000	0.01	32.19	0.39	1.03
2010	2.73	32.78	89.53	239.05
2015	4.44	32.68	145.09	387.39
2016	4.44	35.11	155.87	416.17
Total			**1,164.29**	**3,108.65**

Assumption: baseline fuel usage is the 1997 level of 46.6 litres/ha

US maize: potential additional soil carbon sequestration (1998 to 2016)

	Annual increase in carbon sequestered based on 1997 average (kg carbon/ha)	Crop area (million ha)	Additional carbon sequestered (million kg)	Additional carbon dioxide sequestered (million kg)
1997	0.0	32.2	0.00	0.00
1998	–2.8	32.4	–90.93	–333.70
2000	0.5	32.2	15.56	57.11
2010	28.3	32.8	928.21	3,406.54
2015	45.8	32.7	1,497.16	5,494.56
2016	45.8	35.1	1,608.38	5,902.76
Total			**12,141.68**	**44,559.98**

Assumption: carbon sequestration remains at the 1997 level of 80.1 kg carbon/ha/year

Canadian canola: permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1996–2016)

	Annual reduction based on 1996 average 30.6 (l/ha)	Crop area (million ha)	Total fuel saving (million litres)	Carbon dioxide (million kg)
1996	0.0	3.5	0.0	0.00
1997	0.9	4.9	4.3	11.51
2000	0.9	4.9	4.3	11.48
2010	8.8	6.5	57.7	153.93
2015	8.9	8.1	71.5	191.00
2016	8.9	8.1	71.9	191.85
Total			**755.4**	**2,016.81**

Note: fuel usage NT/RT = 17.3 litres/ha CT = 35 litres/ha

Canadian canola: potential additional soil carbon sequestration (1996 to 2016)

	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
2000	3.3	4.9	15.79	57.96
2010	32.5	6.5	211.72	777.00
2015	32.5	8.1	262.70	964.10
2016	32.5	8.1	263.87	968.39
Total			**2,773.92**	**10,180.28**

Note: NT/RT = + 55 kg of carbon/ha/yr CT = −10 kg of carbon/ha/yr

Permanent reduction in global tractor fuel consumption and carbon dioxide emissions resulting from the cultivation of GM IR cotton (1996–2016)

	Total cotton area in GM IR growing countries excluding Burkina Faso, India, Pakistan, Myanmar, Sudan and China (million ha)	GM IR area excluding Burkina Faso, India, Pakistan, Myanmar, Sudan and China (million ha)	Total spray runs saved (million ha)	Fuel saving (million litres)	CO2 emissions saved (million kg)
1996	6.64	0.86	3.45	2.90	7.73
1997	6.35	0.92	3.67	3.09	8.24
2000	7.29	2.43	9.72	8.17	21.81
2010	7.13	4.59	18.37	15.43	41.21
2015	5.00	3.95	15.78	13.26	35.40
2016	5.74	4.63	18.53	15.57	41.57
Total			**250.28**	**210.24**	**561.34**

Notes: assumptions: 4 applications per ha, 0.84 litres/ha of fuel per insecticide application