Environmental impacts of genetically modified (GM) crop use 1996–2014: Impacts on pesticide use and carbon emissions

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ABSTRACT. This paper updates previous assessments of important 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 in the mid 1990s. The adoption of GM insect resistant and herbicide tolerant technology has reduced pesticide spraying by 581.4 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]) by18.5%. 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 2014, this was equivalent to removing nearly 10 million cars from the roads.

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

INTRODUCTION

GM crop technology has been widely used since the mid 1990s in a number of countries and has mainly been used in 4 main crops; canola, maize, cotton and soybean. In 2014, crops containing this type of technology accounted for 48% of the global plantings of these 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 but latterly since 2011) and squash (in the USA since 2004) 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 and soybeans. 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.

In addition, the GM papaya and squash referred to above are resistant to important viruses (eg, ringspot in papaya).

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 toward 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 2014 into the context of earlier developments and updates the findings of earlier analysis presented by the authors (Brookes and Barfoot, 2006, 2007, 2008, 2010, 2011, 2012, 2013, 2014, 2015).

The methodology and analytical procedures in this present discussion are unchanged to allow a direct comparison of the new with earlier data (readers should however, note that some data presented in

this paper are not directly comparable with data presented in previous analysis because the current paper takes into account the availability of new data and analysis, including revisions to data for earlier years), and in order to save readers the chore of consulting these 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

a) *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 2 broad-spectrum herbicides (mostly glyphosate) used in conjunction with one or 2 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, some incidence of weed resistance to glyphosate has occurred (see additional discussion below) and has 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 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 also probably contributed to the emergence of weeds resistant to herbicides like glyphosate and to weed shifts toward those weed species that are not inherently well controlled by glyphosate. As a result, growers of GM HT crops are increasingly being advised to include other herbicides (with different and complementary modes of action) in combination with glyphosate and in some cases to revert to ploughing in their 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 in the last 7–10 y. Compared to several years ago, the amount of herbicide active ingredient applied and number of herbicides used with GM HT crops in many regions has increased, and the associated environmental profile, as measured by the EIQ indicator, deteriorated. This increase in herbicide use relative to several years ago

is often cited by anti GM technology proponents (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 relative to several years ago and that compared to the conventional alternative, the environmental profile of GM HT crop use has 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 (Brookes et al., 2012). It should also be noted that 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 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 1996–2014 and specifically for the latest year examined, 2014.

GM HT Soybean

The environmental impact of herbicide use change associated with GM HT soybean adoption between 1996 and 2014 is summarised in Table 1. Overall, there has been a small net increase in the amount of herbicide active ingredient used (+0.2%), which equates to about 5.5 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 14.1% 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

TABLE 1. GM HT soybean: Summary of active ingredient usage and associated EIQ changes 1996–2014

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	+4.3	+0.5	−9.1
Brazil	+31.8	+3.2	−5.7
US	−32.6	−3.5	−24.1
Canada	−2.6	−7.5	−21.8
Paraguay	+3.3	+5.5	−4.9
Uruguay	+0.66	+5.7	−7.3
South Africa	−0.3	−4.7	−19.8
Mexico	−0.02	−1.0	−4.7
Bolivia	+1.0	+5.5	−2.9
Aggregate impact: all countries	+5.52	+0.2	−14.1

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

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 plus one or 2 additional, complementary herbicides targeted at weeds that are difficult to control with glyphosate.

In 2014, the amount of herbicide active ingredient applied to the global GM HT soybean crop increased by 7.8 million kg (+3.3%) 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 2014 GM HT soybean crop continued to represent an improvement relative to the conventional alternative (a 10% improvement).

GM HT Maize

The adoption of GM HT maize has resulted in a significant reduction in the volume of herbicide active ingredient usage and an improvement in the associated environmental impact, as measured by the EIQ indicator, between 1996 and 2014 (Table 2).

In 2014, the reduction in herbicide usage relative to the amount reasonably expected if this crop area had been planted to conventional cultivars was 13.2 million kg of active ingredient (−6%), with a larger environmental improvement, as measured by the EIQ indicator of 12.1%. As with GM HT soybeans, the greatest environmental gains have been in developed countries (eg, the 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 23.1 million kg over the 1996–2014 period (Table 3). This represents a 7.3% reduction in usage, and, in terms of the EIQ indicator, a 9.9% net environmental improvement. In 2014, the use of GM HT cotton technology cotton resulted in a 1.8 million kg reduction in herbicide active ingredient use (−8.9%) 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 15% environmental improvement.

TABLE 2. GM HT maize: Summary of active ingredient usage and associated EIQ changes 1996–2014

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
US	−193.1	−9.9	−13.9
Canada	−9.1	−16.4	−19.4
Argentina	−1.9	−1.5	−7.2
South Africa	−2.2	−2.2	−6.4
Brazil	−7.3	−2.5	−7.2
Uruguay	−0.1	−0.7	−10.4
Aggregate impact: all countries	−213.7	−8.4	−12.6

Notes:

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

2. Other countries using GM HT maize – Colombia, Paraguay and the Philippines, not included due to lack of data. Also, hand weeding is likely to be an important form of weed control in the Philippines suggesting any reduction in herbicide use with GM HT maize has been limited.

Other HT Crops

GM HT canola (tolerant to glyphosate or glufosinate) has been grown in Canada, the US, and more recently Australia, while GM HT sugar beet is grown in the US and Canada. The environmental impacts associated with changes in herbicide usage on these crops in the period 1996–2014 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 9.9%, as measured by the EIQ indicator.

In respect of GM HT sugar beet, the adoption of GM HT technology has resulted in a change in herbicide usage away from several applications of selective herbicides to fewer applications of, typically, a single herbicide (glyphosate). Over the period 2008–2014, the widespread use of GM HT technology in the US and Canadian sugar beet crops has resulted in a net increase 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 largely neutral (in other words, no significant change in the EIQ value).

In 2014, the use of GM HT canola resulted in a 2.7 million kg reduction in the amount of herbicide active ingredient use (−19%) relative to the amount reasonably expected if this crop

TABLE 3. GM HT cotton summary of active ingredient usage and associated EIQ changes 1996–2014

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
US	−16.0	−5.8	−8.1
South Africa	+0.01	+1.0	−7.6
Australia	−2.3	−10.3	−13.7
Argentina	−4.7	−28.0	−31.8
Aggregate impact: all countries	−23.01	−7.3	−9.9

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 1996–2014

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
GM HT canola			
US	−2.9	−33.9	−47.0
Canada	−18.3	−18.6	−31.5
Australia	−0.5	−2.8	−2.3
Aggregate impact: all countries	−21.7	−17.2	−29.3
GM HT sugar beet			
US and Canada	+2.0	+32.5	+0.1

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.

area had been planted to conventional canola. More significantly, there was an improvement in associated environmental impact, as measured by the EIQ indicator of 39.4%. The use of GM HT technology resulted in a net additional 0.37 million kg of herbicide active ingredient being applied to the sugar beet crops in the US and Canada (+41%) relative to the amount reasonably expected if this crop area had been planted to conventional sugar beet. This also resulted in a net deterioration in the associated environmental impact (+6.5%) 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 March 2016) 35 weeds species resistant to glyphosate of which many are not associated with glyphosate tolerant crops (www.weedscience.org). In the US, there are currently 16 weeds recognized as exhibiting resistance to glyphosate, of which 2 are not associated with glyphosate tolerant crops. In addition, 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 12 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 0.56 million ha in 2014). In Argentina, Brazil and Canada, where GM HT crops are widely grown, the number of weed species exhibiting resistance to glyphosate are respectively 7, 7 and 5. A few of the glyphosate-resistant species, such as marestail (*Conyza canadensis*), waterhemp (*Amaranthus tuberculatus*) and palmer pigweed (*Amaranthus palmeri*) in the US, are now reasonably widespread, with the affected area being possibly within a range of 35%–50% 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 (www.weedscience.org), and reports of herbicide resistant weeds pre-date the use of GM HT crops by decades. There are, for example, 158 weed species that are resistant to ALS herbicides and 73 weed species resistant to photosystem II inhibitor herbicides.

Where farmers are faced with the existence of weeds resistant to glyphosate in GM HT

crops, they are increasingly being advised to be more proactive and include other herbicides (with different and complementary modes of action) in combination with glyphosate and in some cases to revert to ploughing in 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 already influenced the mix, total amount, cost and overall profile of herbicides applied to GM HT crops in the last 7–10 y.

For example, in the 2014 US GM HT soybean crop, 74% of the GM HT soybean crop received an additional herbicide treatment of one of the following (4 most used, after glyphosate) active ingredients 2,4-D (used pre crop planting), chlorimuron, flumioxazin and sulfentrazone (each used primarily after crop planting). This compares with 14% of the GM HT soybean crop receiving a treatment of one of these 4 herbicide active ingredients in 2006. As a result, the average amount of herbicide active ingredient applied to the GM HT soybean crop in the US (per hectare) increased by about 64% 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 2014, glyphosate accounted for a lower share of total active ingredient use on the GM HT crop (73%) than in 1998 when it accounted for 82% of total active ingredient use, highlighting that farmers continue to realize 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 84% over the same period (2006–2014) 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 5 most used herbicides (trifluralin, acetochlor, S metolachlor, fomesafen and pendimethalin). This compares with 2006, when only 3-quarters of the glyphosate tolerant crop received at least one treatment from the next 5 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 2014. This suggests that US cotton farmers are increasingly adopting current/recent recommended practices for managing weed resistance (to glyphosate).

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

b) *GM IR crops*

The main way in which these technologies have impacted on the environment has been through reduced insecticide use between 1996 and 2014 (Tables 5 and 6). While the adoption of GM HT crops resulted in a shift in the profile of herbicides used, the GM IR technology has effectively replaced 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

TABLE 5. GM IR maize: Summary of active ingredient usage and associated EIQ changes 1996–2014

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
US	−61.6	−46.6	−49.5
Canada	−0.67	−88.0	−62.1
Spain	−0.54	−36.1	−20.5
South Africa	−1.6	−66.0	−66.0
Brazil	−15.2	−86.8	−86.8
Colombia	−0.15	−62.6	−62.6
Aggregate impact: all countries	−79.76	−51.6	−55.7

Notes:

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

2. Other countries using GM 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 various 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.

regimes of insecticides were common place to control bollworm/budworm pests. In maize, the insecticide use savings have tended to be 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 can be found in places 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 2014 were, 8 million kg

TABLE 6. GM IR cotton: Summary of active ingredient usage and associated EIQ changes 1996–2014

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
US	−17.0	−21.6	−17.9
China	−123.6	−30.5	−30.6
Australia	−18.0	−33.2	−34.2
India	−87.0	−26.7	−34.2
Mexico	−1.5	−11.4	−11.3
Argentina	−1.1	−17.1	−24.2
Brazil	−0.8	−10.7	−14.4
Aggregate impact: all countries	−249.0	−27.9	−30.4

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.

(−71% of insecticides typically targeted at maize stalk boring and rootworm pests) and 21.7 million kg (−48.2% 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 2014 were 88.7% associated with insecticide use targeted at maize stalk boring and rootworm pests and 48.2% associated with cotton insecticides. Cumulatively since 1996, the gains have been a 79.8 million kg reduction in maize insecticide active ingredient use and a 249 million kg reduction in cotton insecticide active ingredient use (Tables 5 and 6).

In 2014, IR soybeans were in their second year of commercial use in South America (mostly Brazil). In the first 2 y of use, the insecticide use (active ingredient) saving relative to the amount reasonably expected if this crop area had been planted to conventional soybeans was 1.52 million kg (0.9% of total soybean insecticide use for these 2 years), with an associated environmental benefit, as measured by the EIQ indicator saving of 2.7%.

c) *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 581.4 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 18.5%. In 2014, the environmental benefit was equal to a reduction of 40.4 million kg of pesticide active ingredient use (−6.4%), with the environmental impact associated with insecticide and herbicide use on these crops, as measured by the EIQ indicator, improving by 17.6%.

At the country level, US farms have seen the largest environmental benefits, with a 321 million kg reduction in pesticide active ingredient use (55% 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 4 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 211 million kg (1996–2014).

Results: Greenhouse Gas Emission Savings

a) *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 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 2014, this amounted to a saving of about 2,396 million kg of carbon dioxide, arising from reduced fuel use of 898 million liters (Table 7). These savings are equivalent to taking 1.07 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 (73% of total savings). These savings have been greatest in South America.

Over the period 1996 to 2014, the cumulative permanent reduction in fuel use has been about 21,688 million kg of carbon dioxide, arising from reduced fuel use of 8,123 million liters. In terms of car equivalents, this is equal to taking 9.64 million cars off the road for a year.

b) *Additional soil carbon storage/ sequestration*

As indicated earlier, the widespread adoption and maintenance of RT/NT production systems in North and South America,

TABLE 7. Carbon storage/sequestration from reduced fuel use with GM crops 2014

Crop/trait/country	Fuel saving (million liters)	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	137	366	163
Canada: GM HT soybeans	18	48	21
Argentina: GM HT soybean	282	754	335
Brazil GM HR soybean	180	481	214
Bolivia, Paraguay, Uruguay: GM HT soybean	68	180	80
US: GM HT maize	65	173	77
Canada: GM HT maize	7	18	8
Canada: GM HT canola	74	197	88
Global GM IR cotton	14	37	17
Brazil IR maize	30	80	36
Us/Canada/Spain/South Africa: IR maize	4	12	5
South America: IR soybeans	19	50	22
Total	*898*	*2,396*	*1,066*

Notes:

1. Assumption: an average family car produces 150 g of carbon dioxide per km. A car does an average of 15,000 km/year and therefore produces 2,250 kg of carbon dioxide/year.

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

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, an extra 5,450 million kg of soil carbon is estimated to have been sequestered in 2014 (equivalent to 20,000 million kg of carbon dioxide that has not been released into the global atmosphere). These savings are equivalent to taking 8.9 million cars off the road for one year (Table 8).

The additional amount of soil carbon sequestered since 1996 has been equivalent to 186,945 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 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

TABLE 8. Context of carbon sequestration impact 2014: 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	507	1,860	827
Canada: GM HT soybeans	69	253	112
Argentina: GM HT soybean	2,083	7,645	3,398
Brazil GM HR soybean	1,329	4,877	2,168
Bolivia, Paraguay, Uruguay: GM HT soybean	498	1,828	812
US: GM HT maize	679	2,492	1,107
Canada: GM HT maize	14	50	22
Canada: GM HT canola	271	995	442
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	*5,450*	*20,000*	*8,888*

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 186,945 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 2014 are equal to about 22,396 million kg, equivalent to taking 9.95 million cars off the road for a year. This is roughly equal to 34% of registered cars in the UK.

CONCLUSIONS

During the last 19 years, the adoption of crop biotechnology by many farmers (18 million in 2014) has delivered important positive environmental contributions through its facilitation and evolution of environmentally friendly farming practices. More specifically:

- The environmental gains from the GM IR traits have mostly derived from decreased use of insecticides;
- The gains from GM HT traits have come from a combination of effects. In terms of the environmental impact associated with herbicide use, important changes in the profile of herbicides used have occurred, in favor of more environmentally benign products. Secondly, the technology has facilitated changes in farming systems, by

enabling farmers to capitalise on the availability of a low cost, broad-spectrum herbicide (glyphosate) and move away from conventional to RT/NT production systems in both North and South America. This change in production system has reduced levels of GHG emissions from reduced tractor fuel use and additional soil carbon sequestration.

In relation to GM HT crops, however, over reliance on the use of glyphosate by some farmers, in some regions, has contributed to the development of weed resistance. As a result, farmers have over the last 7–10 years, adopted a mix of reactive and proactive weed management strategies incorporating a mix of herbicides. As a result, some 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 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 (Klumper and Qaim, 2014; Fernandez-Cornejo et al., 2014).

METHODOLOGY

The available literature examining the environmental impact of pesticide use change and implications for greenhouse gas emissions associated with the adoption of GM crops is more limited than the literature examining the economic impacts associated with use of the technology.

This analysis draws on a combination of this literature and a significant amount of 'authors' own analysis' of farm level changes in husbandry practices and pesticide usage data. In particular, readers should note that the analysis of the environmental impact of pesticide usage changes with GM crops includes consideration of measures taken by farmers to address issues of weed resistance 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 (Qaim and De Janvry, 2005; Qaim and Traxler, 2002; Pray et al., 2002), with even fewer (Brookes 2003; Brookes 2005), providing data to the pesticide (active ingredient) level. Secondly, national level pesticide usage survey data is also extremely limited; in fact 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 also conducts pesticide usage surveys but these are not conducted on an annual basis (eg, the last time maize was included was 2014 and previous to this, in 2010 and 2005) and do not disaggregate usage by production type (GM vs. conventional).

Even where national pesticide use survey data is available, it is often of limited value. A reasonable estimate of the amount of herbicide or insecticide usage changes that have occurred with GM crop technology, requires an assessment of what herbicides/insecticides might reasonably be expected to be used in the absence of crop biotechnology on the relevant crops (ie, if the entire crops used non GM production methods). Applying usage rates for the current (remaining) conventional crops is one approach, however, this

invariably provides significant under esti-mates of what usage might reasonably be in the absence of crop biotechnology, because the conventional cropping dataset used to identify pesticide use relates to a relatively small 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 2014, the conventional share (not using GM HT technology) of each crop was only 6%, 7%, 4% and 6% respec-tively 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 cot-ton and canola crops, and since 2007 for the maize crop (source: USDA - note the con-ventional share refers to not using GM HT technology, with some of the 'conventional crops' using crop biotechnology-traited seed providing GM insect resistance only).

The reasons why this conventional cropping data set is unrepresentative of the levels of herbi-cide/insecticide use that might reasonably be expected in the absence of biotechnology include:

- While the degree of pest/weed problems/ damage vary by year, region and within region, farmers' who continue to farm conventionally may be those with rela-tively low levels of pest/weed problems, and hence see little, if any economic bene-fit from using the GM traits targeted at minimal pest/weed problems. In addition, late or non adopters of new technology in agriculture are typically those who gener-ally make less use of newer technologies than earlier adopters. As a result, insecti-cide/herbicide usage levels for these non adopting farmers tends 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 con-ventional seed generally use extensive, low intensity production methods (includ-ing 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 tech-nology has resulted in 'area-wide' sup-pression 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 conduct insecticide treatments (Hutchison et al., 2010).
- Some of the farmers using GM traits have experienced improvements in pest/weed control from using this technology relative to the conventional control methods previ-ously used. If these farmers were to now switch back to using conventional techni-ques, it is likely that most would wish to maintain the levels of pest/weed control delivered with use of the GM traits and therefore some would use higher levels of insecticide/herbicide than they did in the pre GM crop days. This argument can, however, be countered by the constraining influence on farm level pesticide usage that comes from the cost of pesticides and their application. Ultimately the decision to use more pesticide or not would be made at the farm level according to indi-vidual assessment of the potential benefits (from higher yields) compared to the cost of additional pesticide use.

This problem of poor representativeness of the small conventional dataset has been addressed by firstly, using the average recorded values for insecticide/herbicide usage on con-ventional crops for years only when the con-ventional 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 US crop was no longer using crop biotechnology, based on opinion from extension and industry advisors across the US as to what farmers might reasonably be expected to use in terms of weed control practices and usage levels of

insecticide/herbicide. In addition, the usage levels identified from this methodology were cross checked (and subject to adjustment) against historic average usage levels of key herbicide and insecticide active ingredients from the private market research data set so as to minimise the scope for overstating likely usage levels on the conventional alternative. Overall, this approach has been applied in other countries where pesticide usage data is available, though more commonly, because of the paucity of available data, the analysis relies more on extension/advisor opinion and knowledge of actual and potential pesticide use.

This methodology has been used by others (Sankula and Blumenthal, 2003; Sankula and Blumenthal, 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 management practices and technologies rather than making comparisons solely on past practices. Details of how this methodology has been applied to the 2014 calculations, sources used for each trait/country combination examined and examples of typical conventional versus GM pesticide applications are provided in Appendices 1 and 2.

The most common way in which environmental impact associated with pesticide use changes with GM crops has typically been presented in the literature has been in terms of the volume (quantity) of pesticide applied. However, while the amount of pesticide applied to a crop is one way of trying to measure the environmental impact of pesticide use, this is not a good measure of environmental impact because the toxicity of each pesticide is not directly related to the amount (weight) applied. For example, the environmental impact of applying a kilogram of dioxin to a crop is far more toxic than applying a kilogram of salt. There exist alternative (and better) measures that have been used by a number of authors of peer reviewed papers to assess the environmental impact of pesticide use change with GM crops rather than simply looking at changes in the volume of active ingredient applied to crops. In

particular, there are a number of peer reviewed papers that utilize the Environmental Impact Quotient (EIQ) developed at Cornell University by Kovach et al. (1992) and updated annually. 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 vs. GM crop production systems, with the total environmental impact or load of each system, a direct function of respective field EIQ/ha values and the area planted to each type of production (GM versus conventional). The use of environmental indicators is commonly used by researchers and the EIQ indicator has been, for example, cited by Brimner et al. (2004, 2005) in a study comparing the environmental impacts of GM and conventional canola and by Kleiter et al. (2005). 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:

- Summarizes 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). 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 labor 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 the EIQ as an indicator of the environmental impact of pesticide use change with GM crops because it is, in our view, a superior indicator to only using amount of pesticide active ingredient applied. 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 vs. conventional crops for the year 2014 are presented in Appendix 2.

Methodology: Impact of Greenhouse Gas Emissions

The methodology used to assess impact on greenhouse gas emissions combines reviews of literature relating to changes in fuel and tillage systems and carbon emissions, coupled with evidence from the development of relevant GM crops and their impact on both 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; Leibig et al., 2005; West and Post 2002; Derpsch et al., 2010; Eagle et al., 2012; Olson et al., 2013).

First, GM crops contribute to a reduction in fuel use due to less frequent herbicide or insecticide applications and a reduction in the energy use in soil cultivation. For both herbicide and insecticide spray applications, the quantity of energy required to apply the pesticides depends upon the application method. For example, in the USA, a typical method of application is with a 50 foot boom sprayer which consumes approximately 0.84 liters/ha (Lazarus, 2013). In terms of GHG, each liter of tractor diesel consumed contributes an estimated 2.67 kg of carbon dioxide into the atmosphere (so 1 less spray run reduces carbon dioxide emissions by 2.24 kg/ha). Given that many farmers apply insecticides via sprayers pulled by tractors, which tend to 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 conventional tillage (CT) to reduced/no till (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 cultivars and RT/NT production systems. For example, there has been a 50% increase in the RT/NT soybean area in the US and a 7-fold increase in Argentina since 1996. In 2014, RT/NT production accounted for 86% 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 2014, accounted for 85% of the total crop (90% the RT/NT canola area is planted with GM HT cultivars).

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 (2013). In the analysis 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 liters/ha compared with traditional conventional tillage and in the case of RT (mulch till) cultivation by 10.39 liters/ha. In the case of maize, NT results in a saving of 24.41 liters/ha and 7.52 liters/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. A number of researchers have examined the relationship between carbon sequestration and different tillage systems (Intergovernmental Panel on Climate Change, 2006; Robertson et al., 2000; Johnson et al., 2005; Leibig et al., 2005; Calegari et al., 2000; Baker et al., 2007; Angers and Eriksen-Hamel, 2008; Blanco-Canqui and Lal, 2008; Lal, 2004, 2005, 2010; Bernacchi, 2005; Michigan State University, 2016). This literature shows that the amount of carbon sequestered varies by soil type, cropping system, eco-region and tillage depth. It also shows that tillage systems can impact on levels of other GHG emissions such as methane and nitrous oxide and on crop yield.

Overall, the literature highlights the difficulty in estimating the contribution NT/RT systems can make to soil carbon sequestration, especially because of the dynamic nature of soils, climate, cropping types and patterns. If a specific crop area is in continuous NT crop rotation, the full soil carbon sequestration benefits described in the literature can be realized. 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 further 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, the rate of carbon sequestration in GM HT may be declining. Our estimates presented in this paper, however, assume that a constant rate of carbon sequestration occurs because of the relatively short time period that NT/RT production systems have been operated (and hence 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 (ie, parts of Brazil).

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

DISCLOSURE OF POTENTIAL CONFLICTS OF INTEREST

FUNDING

REFERENCES

American Soybean Association Conservation Tillage Study. 2001. Available on the Worldwide Web at Http://soygrowers.com/ctstudy/ctstudy_files/frame.htm

Angers DA, Eriksen-Hamel NS. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci Soc Am J 2008; 72:1370–4; http://dx.doi.org/10.2136/sssaj2007.0342

Asia-Pacific Consortium on Agricultural Biotechnology (APCoAB). Bt cotton in India: a status report, ICRA-STAT, New Delhi, India. 2006.

Baker J, Ochsner T, Venterea T, Griffis T. Tillage and soil carbon sequestration—What do we really know? Agr Ecosyst Environ 2007; 118:1–5; http://dx.doi.org/10.1016/j.agee.2006.05.014

Benbrook C. A review and assessment of impact of genetically engineered crops on pesticide use in the US – the first sixteen years. Environ Sci Eur 2012; 24:24; http://dx.doi.org/10.1186/2190-4715-24-24

Bernacchi, et al. The conversion of the corn/soybean ecosystem to no-till agriculture may result in a carbon sink. Glob Change Biol 2005; 11(11):1867–72.

Blanco-Canqui H, Lal R. No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci Soc Am J 2008; 72:693–701; http://dx.doi.org/10.2136/sssaj2007.0233

Brimner T, Gallivan G, Stephenson G. Influence of herbicide-resistant canola on the environmental impact of weed management. Pest Manag Sci 2005; 61(1):47–52; PMID:15593073; http://dx.doi.org/10.1002/ps.967

Brookes G. The benefits of adopting GM insect resistant (Bt) maize in the EU: First results from 1998–2006. Int J Biotechnol 2008; 10(2/3):148–166.

Brookes G. The farm level impact of using Bt maize in Spain. Paper presented at the 6th International Consortium on Agricultural Biotechnology Research (ICABR) Conference, Ravello, Italy. 2003. Available on the World Wide Web: http://www.pgeconomics.co.uk/pdf/bt_maize_in_spain.pdf

Brookes G. The farm-level impact of herbicide-tolerant soybeans in Romania. AgBioForum 2005; 8(4):235–41. Available on the World Wide Web: http://www.agbioforum.org

Brookes G, Barfoot P. Global impact of biotech crops: socio-economic and environmental effects 1996–2004. AgbioForum 2006; 8(2&3):187–96; Available on the World Wide Web: http://www.agbioforum.org

Brookes G, Barfoot P. Global impact of biotech crops: socio-economic and environmental effects 1996–2005. Agbioforum 2007; 9 (3):1–13; Available on the World Wide Web: http://www.agbioforum.org

Brookes G, Barfoot P. Global impact of biotech crops: socio-economic and environmental effects 1996–2006. Agbioforum 2008; 11(1):21–38; Available on the World Wide Web: http://www.agbioforum.org

Brookes G, Barfoot P. Global impact of biotech crops: environmental effects 1996–2008. AgBioForum 2010; 13(1):76–94; Available on the World Wide Web: http://www.agbioforum.org

Brookes G, Barfoot P. Global impact of biotech crops: environmental effects 1996–2009. GM Crops 2011; 2 (1):34–49; PMID:21844697

Brookes G, Barfoot P. Global impact of biotech crops: environmental effects 1996–2010. GM Crops 2012; 3:1–9; http://dx.doi.org/10.4161/gmcr.19925

Brookes G, Barfoot P. Key environmental impacts of global GM crop use 1996–2011. GM Crops 2013; 4:1–11; http://dx.doi.org/10.4161/gmcr.22748

Brookes G, Barfoot P. Key environmental impacts of GM crops 1996–2012. GM Crops 2014; 5:149–60; http://dx.doi.org/10.4161/gmcr.28449

Brookes G, Barfoot P. Environmental impacts of GM crop use 1996–2013: impacts on pesticide use and carbon emissions. GM Crops 2015; 6(2):103–33.

Brookes G, Carpenter J, McHughen A. A review and assessment of Impact of genetically engineered crops on pesticide use in the US – the first sixteen years' by Benbrook C. 2012. www.pgeconomics.co.uk

Calegari A, Hargrove W, Rheinheimer D, Ralisch R, Tessier D, De Tourfonnet S, Guimaraes Ml. Impact of long-term no-tillage and cropping system management on soil organic carbon in an Oxisil: A model for sustainability. Agron J 2000; 100; 1013–9; http://dx.doi.org/10.2134/agronj2007.0121

Commonwealth Scientific and Industrial Research Organisation (CSIRO). The cotton consultants Australia 2005 Bollgard II comparison report. Collingwood, Australia. 2005.

Canola Council of Canada. An agronomic & economic assessment of transgenic canola, Canola Council, Canada. 2001. Available on the Worldwide Web: http://www.canola-council.org

Conservation Tillage and Plant Biotechnology (CTIC). How new technologies can improve the environment by reducing the need to plough. 2002. Available on the World Wide Web: http://www.ctic.purdue.edu/CTIC/Biotech.html

Derpsch R, Friedrich T, Kassam A, Hongwen L. Current status of adoption on no-till farming in the world and some of its main benefits. Int J Agric & Biol Eng 2010; 3(1):1–26.

Doyle B. The performance of Ingard and Bollgard II cotton in Australia during the 2002/2003 and 2003/2004 seasons. Armidale, Australia: University of New England. 2005

Doyle B. The performance of roundup ready cotton 2001–2002 in the Australian cotton sector. Armidale, Australia: University of New England. 2003

Eagle J, Olander L, Henry L, Haugen-Kozyra K, Millar N, Robertson P. Greenhouse Gas Mitigation potential of agricultural land management in the United States - A synthesis of the literature 2012 (3rd ed.). Duke University Technical Working Group on Agricultural Greenhouse Gases (T-AGG) Report.

Fabrizzi K, Moron A, Garan F. Soil carbon and nitrogen organic fractions in degraded vs non-degraded molli-sols in argentina. Soil Sci Soc Am J 2003. 67:1831–41; http://dx.doi.org/10.2136/sssaj2003.1831

Fernandez-Cornejo J, Wechsler S, Livingston M, Mitchell L. Genetically engineered crops in the United States. 2014. USDA Economic Research Service report ERR 162. www.ers.usda.gov

Fisher J, Tozer P. Evaluation of the environmental and economic impact of Roundup Ready Canola in the Western Australian Crop Production System. Curtin University of Technology. 2009. Technical report 11/2009, ISBN 9780 9807333-0-3

Galveo A. Farm survey findings of impact of insect resistant cotton in Brazil, Celeres, Brazil. 2009 & 2010. www.celeres.br

Galveo A. Farm survey findings of impact of GM crops in Brazil 2011, Celeres, Brazil. 2012. www.celeres.co.br

George Morris Centre. Economic & environmental impacts of the commercial cultivation of glyphosate tolerant soybeans in Ontario (unpublished report). Guelph, Ontario: Author. 2004

Gianessi L, Carpenter, J. Agricultural biotechnology: Insect control benefits. Washington, DC: NCFAP. 1999. Available on the World Wide Web: http://www.ncfap.org/reports/biotech/insectcontrolbenefits.pdf

Hutchison W, Burkness EC, Mitchell PD, Moon RD, Leslie TW, Fleischer SJ, Abrahamson M, Hamilton KL, Steffey KL, Gray ME, et al. Area-wide suppression of European Corn Borer with Bt maize reaps savings to non-bt maize growers. Science 2010; 330:222–5; PMID:20929774; http://dx.doi.org/10.1126/science.1190242; www.sciencemag.org

IMRB International. Socio-economic benefits of Bollgard and product satisfaction (in India). Mumbai, India: Author. 2006

IMRB International. Socio-economic benefits of Bollgard and product satisfaction in India. Mumbai, India: Author. 2007

Intergovernmental Panel on Climate Change. Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories. Guidelines for National Greenhouse Gas Inventories Volume 4. Agriculture, Forestry and Other Land Use. 2006. Available on the World Wide Web: http://www.ipccnggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_02_Ch2_Generic.pdf

Ismael Y, Bennett R, Morse S, Buthelezi T. Bt Cotton and pesticides. A case study of smallholder farmers in Makhathini Flats South Africa. Paper presented at the International ICABR Conference, Ravello, Italy. 2002.

Jasa P. Conservation Tillage Systems, Extension Engineer, University of Nebraska. 2002.

Johnson J, Reicosky D, Allmarao R, Sauer T, Venterea R, Dell C. Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil Till Res 2005; 83:73–94; http://dx.doi.org/10.1016/j.still.2005.02.010

Johnson S, Strom S. Quantification of the impacts on US agriculture of biotechnology-derived crops planted in 2006. Washington, DC: National Center for Food and Agricultural Policy (NCFAP). 2007. Available on the Worldwide Web: http://www.ncfap.org

Kleiter G. The effect of the cultivation of GM crops on the use of pesticides and the impact thereof on the environment, RIKILT, Institute of Food Safety, Wageningen, Netherlands. 2005

Klumper W, Qaim M. A meta analysis of the impacts of genetically modified crops. Plos One 2014; 9: e111629; PMID:25365303; http://dx.plos.org/10.1371/journal.pone.0111629

Kovach J, Petzoldt C, Degni J, Tette J. A method to measure the environmental impact of pesticides. New York's Food and Life Sciences Bulletin. NYS Agriculture. Exp. Sta. Cornell University, Geneva, NY, 139. 8 pp. 1992 and annually updated. Available on the Worldwide Web: http://www.nysipm.cornell.edu/publications/EIQ.html

Lal R. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degr Dev 2005. 17: 2: 197–209; http://dx.doi.org/10.1002/ldr.696

Lal R. Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food Security, 2010; 2(2):169–77; http://dx.doi.org/10.1007/s12571-010-0060-9

Lal R. Soil carbon sequestration impacts on global climate change and food security. Science 2004; 304 (5677):1623–7; PMID:15192216; http://dx.doi.org/10.1126/science.1097396

Lazarus WF. Machinery Cost Estimates May 2013, University of Minnesota Extension Service.

Leibig M, Morgan J, Reeder J, Elert B, Gollany H, Schuman G. Greenhouse gas contributions and mitigation potential of agriculture practices in north-western USA and Western Canada. Soil Till Res 2005; 83:25–52; http://dx.doi.org/10.1016/j.still.2005.02.008

Michigan State University. US Cropland greenhouse gas calculator. 2016. Available from: http://surf.kbs.msu.edu

Monsanto Brazil. Farm survey of conventional and Bt cotton growers in Brazil 2007 (unpublished). 2008.

Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2005 cotton crop, unpublished. 2005.

Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2007 cotton crop, unpublished. 2007.

Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2008 cotton crop, unpublished. 2008.

Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2009 cotton crop, unpublished. 2009.

Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2011 cotton crop, unpublished. 2012.

Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2011 cotton crop, unpublished. 2013.

Olson K, Ebelhar S, Lang J. Effects of 24 years of conservation tillage systems on soil organic carbon and soil productivity. Appl Environ Soil Sci 2013; Article ID 617504; PMID:26949393; http://dx.doi.org/10.1155/2013/617504

Peterson R, Schleier J. A probabilistic analysis reveals fundamental limitations with the environmental impact quotient and similar systems for rating pesticides. PeerJ 2014; 2:e364; PMID:24795854; http://dx.doi.org/10.7717/peerj.364

Pray C, Huang J, Hu R, Roselle S. Five years of Bt cotton in China – the benefits continue. Plant J 2002; 31 (4):423–30; PMID:12182701; http://dx.doi.org/10.1046/j.1365-313X.2002.01401.x

Qaim M, De Janvry A. Bt cotton and pesticide use in Argentina: economic and environmental effects. Environ Dev Econ 2005; 10:179–200; http://dx.doi.org/10.1017/S1355770X04001883

Qaim M, Traxler G. Roundup Ready soybeans in Argentina: farm level, environmental and welfare effects, 6th ICABR conference. 2002. Ravello, Italy

Reeder R. No-till benefits add up with diesel fuel savings. 2010 http://www.thelandonline.com/currentedition/x1897235554/No-till-benefits-add-up-with-diesel-fuel-savings

Reicosky D. Conservation tillage and carbon cycling: soil as a source or sink for carbon University of Davis, USA. 1995.

Robertson G, Paul E, Harwood R. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radioactive forces of the atmosphere. Science 2000; 289; N^0 (5486):1922–5; PMID:10988070; http://dx.doi.org/10.1126/science.289.5486.1922

Sankula S, Blumenthal E. Impacts on US agriculture of biotechnology-derived crops planted in 2003: An update of eleven case studies. Washington, DC: NCFAP. 2003. Available on the World Wide Web: http://www.ncfap.org

Sankula S, Blumenthal E. Impacts on US agriculture of biotechnology-derived crops planted in 2005: An update of eleven case studies. Washington, DC: NCFAP. 2006. Available on the World Wide Web: http://www.ncfap.org; PMID:NOT_FOUND

Smyth SJ, Gusta M, Belcher K, Phillips PWB, Castle D. Changes in herbicide use following the adoption of HR canola in western Canada. Weed Technology 2011; 25(3):492–500.

Traxler G, Godoy-Avilla S, Falck-Zepeda J, Espinoza-Arellano J. Transgenic cotton in Mexico: Economic and environmental impacts. Paper presented at the 5th International Conference on Biotechnology, Science and Modern Agriculture: A new industry at the dawn of the century, Ravello, Italy. 2001

University of Illinois. Costs and fuel use for alternative tillage systems. 2006. Available on the World Wide Web: http://www.farmdoc.uiuc.edu/manage/newsletters/fefo0607/fefo0607.html

USDA Comet-VR. An online tool for estimating carbon storage in agroforestry practices. 2013. www.cometvr.colostate.edu

USDA Energy Estimator: tillage. 2013 http://ecat.sc.egov.usda.gov

West T, Post W. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Analysis. Soil Sci Soc Am J 2002; 66 November/December: 930–1046; http://dx.doi.org/10.2136/sssaj2002.1930

Appendix 1: Details of Methodology as Applied to 2014 Calculations of Environmental Impact Associated with Pesticide Use Changes

GM IR maize (targeting stalk boring pests) 2014

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	26,916	3,364	0.23	0.58	12.8	22.8	−1,178	−33.6
Canada	1,031	61	0.04	0.64	4.8	24.8	−36	−1.0
Argentina	4,399	0	0	0	0	0	0	0
Philippines	602	Very low – assumed zero	0	0	0	0	0	0
South Africa	2,653	1,768	0	0.09	0	3.2	−165	−6.0
Spain	132	43.9	0.36	1.32	0.9	26.9	−402	−1.1
Uruguay	76	Assumed to be zero: as Argentina	0	0	0	0	0	0
Brazil	11,910	7,595	0 targeted at stalk boring pests	0.36 targeted at stalk boring pests	0 targeting stalk boring pests	21.5	−2,704	−163
Colombia	66.8	48	0 targeted at stalk boring pests	0.56 targeted at stalk boring pests	0 targeting stalk boring pests	15.9	−27	−0.76

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) 2014

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	18,673	9,733	0.2	0.6	12	32.5	−3,893	−199.5

Notes:

1. There are no Canadian-specific data available: analysis has therefore not been included for the Canadian crop of 734,000 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 2014 maximum area on which this calculation is made has been reduced by 360,000 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 2014

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	3,113	0.85	1.84	22.5	41.6	−2,795	−59.6
China	4,092	2.10	3.48	87.0	122.5	−5,618	−145.5
Australia	196	0.91	2.1	25.0	65.0	−233	−7.8
Mexico	100	3.60	5.22	120.4	177.0	−162	−5.7
Argentina	362	0.7	2.42	19.9	76.7	−118	−8.3
India	11,684	0.63	1.77	18.8	74.8	−12,645	−654.1
Brazil	330	0.41	0.736	15.1	38.2	−108	−7.6

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 2014

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	31,419	2.18	2.19	36.2	42.2	−1,317	−187.8
Canada	1,341	1.32	1.43	20.9	34.2	+147	−17.9
Argentina	19,681	3.11	2.82	48.2	48.7	+5,763	−9.9
Brazil	29,847	2.59	2.53	40.6	47.4	+1,842	−202.0
Paraguay	3,230	3.18	3.03	50.6	51.8	+484	−4.0
South Africa	618	1.08	1.46	16.6	27.11	−236	−6.5
Uruguay	1,320	2.98	2.82	47.5	48.7	+216	−1.7
Bolivia	1,062	3.18	3.03	50.6	51.8	+159	+1.3
Mexico	18	1.62	1.76	24.8	41.0	−3	−0.3

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

GM IR (Intacta) soybeans 2014

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	5,870	1.43	1.6	30.65	47.9	−1,012	−101.3
Paraguay	200	1.43	1.6	30.65	47.9	−34.5	−3.4
Argentina	634	0.23	0.31	7.74	9.0	−50.7	−0.8
Uruguay	250	0.23	0.31	7.74	9.0	−20.0	−0.3

GM HT maize 2014

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	30,243	2.98	3.4	56.4	67.3	−12,658	−327.5
Canada glyphosate tolerant	1,172	1.83	2.71	37.0	61.1	−1,032	−28.4
Canada glufosinate tolerant	12	1.64	2.71	36.0	61.0	−13	−0.3
Argentina	3,801	3.99	3.53	71.8	73.6	+1,763	−6.9
South Africa	1,990	2.85	3.15	53.7	66.1	−597	−25
Brazil	7,980	3.91	3.99	70.3	86.1	−654	−127
Uruguay	76	3.99	3.53	71.8	73.6	+35	−0.1

Notes:

1. Philippines: 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 2014

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	3,372	4.37	4.71	77.7	90.2	−1,151	−44.4
S Africa	15	1.80	1.81	27.6	31.9	−0.2	−0.07
Australia	210	3.10	4.76	51.7	87.5	−350	−7.5
Argentina	412	4.06	4.72	64.0	78.4	−271	−5.9

Note:

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

GM HT canola 2014

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	320	1.16	1.06	17.7	22.9	+30	−1.6
US glufosinate tolerant	278	0.44	1.06	8.8	22.9	−174	−3.9
Canada glyphosate tolerant	3,563	1.16	1.06	17.7	22.9	+340	−18.4
Canada glufosinate tolerant	4,356	0.44	1.06	8.8	22.9	−2,729	−61.4
Australia glyphosate tolerant	350	0.52	14	7.3	22.3	−183	−2.5

GM herbicide tolerant sugar beet 2014

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	455	2.4	1.6	36.8	34.5	+365	+1.0

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 2014

	Active ingredient (kg/ha)	Field EIQ/ha value
GM HT soybean	3.11	48.2
Source: AMIS Global dataset on pesticide use 2014		
Conventional soybean		
Option 1		
Glyphosate	1.62	24.83
Metsulfuron	0.03	0.50
2 4 D	0.30	6.21
Imazethapyr	0.10	1.96
Diflufenican	0.03	0.29
Clethodim	0.19	3.23
Total	**2.27**	**37.03**
Option 2		
Glyphosate	1.62	24.83
Dicamba	0.12	3.04
Acetochlor	1.08	21.49
Haloxifop	0.12	2.66
Sulfentrazone	0.19	2.23
Total	**3.13**	**54.25**
Option 3		
Glyphosate	1.62	24.83
Atrazine	0.87	19.92
Bentazon	0.60	11.22
2 4 D ester	0.04	0.61
Imazaquin	0.024	0.37
Total	**3.154**	**56.96**
Option 4		
Glyphosate	1.8	27.59
2 4 D amine	0.384	7.95
Flumetsulam	0.06	0.94
Fomesafen	0.25	0.13
Chlorimuron	0.01	0.29
Fluazifop	0.12	3.44
Total	**2.63**	**46.34**
Option 5		
Glyphosate	1.8	27.59
Metsulfuron	0.03	0.50
2 4 D amine	0.75	15.53
Imazethapyr	0.1	1.96
Haloxifop	0.12	2.66
Total	**2.80**	**48.24**
Option 6		
Glyphosate	1.8	27.59
Metsulfuron	0.03	0.50
2 4 D amine	0.75	15.53
Imazethapyr	0.1	1.96
Clethodim	0.24	4.08
Total	**2.92**	**49.66**
Average all 6 conventional options	**2.82**	**48.75**

Sources: AAPRESID, AMIS Global, Monsanto Argentina

Typical insecticide regimes for cotton in India 2014

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	0.04	0.57
Total	**1.94**	**79.5**
Option 2		
Imidacloprid	0.06	2.2
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.45
Diafenthiuron	0.1	2.53
Chloripyrifos	0.39	10.58
Profenfos	0.81	48.28
Metaflumizone	0.03	0.82
Emamectin	0.01	0.29
Total	**1.50**	**67.83**
Average conventional	1.73	73.67
GM IR cotton		
Imidacloprid	0.06	2.2
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.45
Diafenthiuron	0.1	2.53
Buprofezin	0.07	2.55
Acephate	0.63	15.79
Total	**0.97**	**26.19**
Option 2		
Imidacloprid	0.06	1.54
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	2.30
Diafenthiuron	0.1	2.53
Total	**0.26**	**8.04**
Weighted average GM IR cotton	**0.68**	**18.85**

Source: Monsanto India, AMIS Global

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

Data sources (for pesticide usage data)

	Sources of data for assumptions
US	Gianessi and Carpenter (1999)
	Sankala and Blumenthal (2003, 2006), Johnson and Strom (2007)
	Own analysis (2010–2013)
	All of the above mainly for conventional regimes (based on surveys and consultations of extension advisors and industry experts)GFK Plant and Animal Health – private market research data on pesticide usage. Is the most comprehensive data set 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

(*Continued*).

Sources of data for assumptions

Country	Sources
Argentina	AMIS Global & Kleffmann - private market research data on pesticide use. Is the most detailed dataset on crop pesticide use AAPRESID (farmer producers association) – personal communications (2007) Monsanto Argentina (personal communications, 2005, 2007, 2009, 2010, 2011, 2012, 2013, 2014) Qaim and De Janvry (2005) Qaim and Traxler (2002)
Brazil	AMIS Global & Kleffmann - private market research data on crop pesticide use. Is the most detailed data set on crop pesticide use Monsanto Brazil (2008), Galveo (2009, 2012), plus personal communications Monsanto Brazil (personal communications, 2007, 2009, 2011, 2013, 2014)
Uruguay	AMIS Global and as Argentina for conventional
Paraguay	As Argentina for conventional soybeans (over the top usage), AMIS Global for GM HT soybean
Bolivia	As Paraguay: no country-specific data identified
Canada	George Morris Center (2004) Canola Council (2001) Smyth et al. (2011) Weed Control Guide Ontario (updated annually)
S Africa	Monsanto S Africa (personal communications, 2005, 2007, 2009, 2010, 2011, 2012, 2014) Ismael et al. (2002) AMIS Global
Romania	AMIS Global, Brookes (2005)
Australia	AMIS Global, Doyle (2003, 2005), CSIRO (2005) Monsanto Australia (personal communications, 2005, 2007, 2009, 2010, 2011, 2012, 2014) Fisher and Tozer (2009)
Spain	Brookes (2003, 2008)
China	AMIS Global Pray et al. (2002) Monsanto China personal communication (2007, 2009, 2010, 2011, 2013, 2014)
Mexico	(Monsanto Comercial Mexico 2013, 2012, 2009, 2008, 2007, 2005) Traxler et al (2001)
India	AMIS Global APCOAB (2006) IMRB (2006, 2007) Monsanto India (2007, 2008, 2009, 2010, 2011, 2013) – personal communications

Appendix 3: Carbon Saving Estimates: Additional Information

US soybeans: Permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1996–2014)

	Annual reduction based on 1996 average (liters/ha)	Crop area (million ha)	Total fuel saving (million liters)	Carbon dioxide (million kg)
1996	0.00	25.98	0.00	0.00
1997	0.40	28.33	11.36	30.33
1998	0.80	29.15	23.38	62.41
1999	0.86	29.84	25.65	68.50
2000	0.92	30.15	27.66	73.86
2001	1.16	29.99	34.94	93.28
2002	1.41	29.54	41.72	111.39
2003	1.91	29.71	56.64	151.23
2004	2.40	30.28	72.69	194.09
2005	2.54	28.88	73.33	195.80
2006	2.68	30.56	81.84	218.51
2007	2.95	25.75	75.85	202.51
2008	2.89	30.21	87.32	233.15
2009	2.89	30.91	89.35	238.56
2010	3.19	31.56	100.54	268.45
2011	3.29	30.05	98.86	263.95
2012	3.56	30.82	109.76	293.05
2013	3.83	30.70	117.66	314.15
2014	4.10	33.42	137.15	366.18
Total			**1,265.70**	**3,379.41**

Assumption: baseline fuel usage is the 1996 level of 36.6 liters/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 2014)

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total additional carbon sequestered (million kg)	Total additional Carbon dioxide sequestered (million kg)
1996	0.0	26.0	0.00	0.00
1997	1.4	28.3	39.33	144.35
1998	2.8	29.1	80.93	297.02
1999	3.1	29.8	91.02	334.06
2000	3.3	30.1	100.23	367.85
2001	4.3	30.0	127.80	469.04
2002	5.2	29.5	153.56	563.58
2003	7.0	29.7	208.80	766.29
2004	8.9	30.3	268.21	984.34
2005	9.5	28.9	272.92	1,001.62
2006	10.0	30.6	306.91	1,126.36
2007	11.1	25.8	284.83	1,045.34
2008	10.9	30.2	327.94	1,203.54
2009	10.9	30.9	335.55	1,231.46
2010	11.9	31.6	374.35	1,373.86
2011	12.2	30.1	365.47	1,341.27
2012	13.2	30.8	405.67	1,488.82
2013	14.2	30.7	434.81	1,595.74
2014	15.2	33.4	506.75	1,859.79
Total			**4,685.10**	**17,194.33**

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 (1996–2014)

	Annual reduction based on 1996 average of 39.1 (liters/ha)	Crop area (million ha)	Total fuel saving (million liters)	Carbon dioxide (million kg)
1996	0.0	5.9	0.0	0.00
1997	2.3	6.4	14.7	39.16
1998	3.1	7.0	21.5	57.39
1999	2.7	8.2	21.9	58.54
2000	3.0	10.6	31.6	84.45
2001	5.8	11.5	67.2	179.41
2002	8.3	13.0	107.3	286.57
2003	9.8	13.5	132.2	352.90
2004	11.7	14.3	167.4	447.02
2005	10.7	15.2	163.0	435.19
2006	11.0	16.2	177.4	473.74
2007	12.3	16.6	204.2	545.15
2008	13.7	16.8	230.4	615.13
2009	13.2	18.6	245.9	656.53
2010	13.7	18.2	249.8	667.06
2011	14.3	18.6	265.5	709.00
2012	14.3	19.4	276.3	737.59
2013	14.3	19.8	282.0	752.84
2014	14.3	19.8	282.4	753.98
Total			**2940.7**	**7851.6**

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

Argentine soybean: Potential additional soil carbon sequestration (1996 to 2014)

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total additional carbon sequestered (million kg)	Total additional Carbon dioxide sequestered (million kg)
1996	0.0	5.91	0.0	0.0
1997	16.92	6.39	108.17	396.98
1998	22.80	6.95	158.52	581.78
1999	19.77	8.18	161.68	593.38
2000	22.03	10.59	233.27	856.09
2001	43.09	11.50	495.53	1,818.58
2002	61.05	12.96	791.51	2,904.83
2003	72.20	13.50	974.71	3,577.19
2004	86.07	14.34	1,234.69	4,531.31
2005	79.08	15.20	1,202.00	4,411.35
2006	81.02	16.15	1,308.48	4,802.13
2007	90.79	16.59	1,505.72	5,526.00
2008	101.33	16.77	1,699.00	6,235.34
2009	97.49	18.60	1,813.37	6,655.06
2010	101.23	18.20	1,842.45	6,761.81
2011	105.28	18.60	1,958.28	7,186.90
2012	105.28	19.35	2,037.25	7,476.69
2013	105.28	19.75	2,079.36	7,631.25
2014	105.28	19.78	2,082.52	7,642.84
Total			**21,686.51**	**79,589.49**

Assumption: NT = +175 kg carbon/ha/yr, CT = −25 kg carbon/ha/yr.

Brazil (3 southernmost states) soybean: Permanent reduction in tractor fuel consumption and reduction in carbon dioxide emissions (1997–2014)

	Annual reduction based on 1997 average of 40.9 (liters/ha)	Crop area (million ha)	Total fuel saving (million liters)	Carbon dioxide (million kg)
1997	0.00	6.19	0.00	0.00
1998	1.36	6.12	8.30	22.15
1999	2.71	6.05	16.40	43.80
2000	4.07	5.98	24.34	65.00
2001	5.42	6.84	37.09	99.03
2002	6.78	7.49	50.76	135.53
2003	8.14	8.21	66.83	178.43
2004	9.49	8.59	81.52	217.65
2005	10.85	8.30	89.98	240.26
2006	12.20	8.25	100.65	268.73
2007	12.20	8.19	99.89	266.71
2008	13.56	8.23	111.56	297.86
2009	14.37	8.90	127.94	341.60
2010	14.92	9.13	136.24	363.75
2011	14.92	9.11	135.83	362.66
2012	15.46	9.88	152.79	407.95
2013	16.27	10.49	170.74	455.87
2014	16.27	11.07	180.20	481.13
Total			**1,591.05**	**4,248.09**

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

Brazil (3 southernmost states) soybean: Potential additional soil carbon sequestration (1997 to 2014)

	Annual increase in carbon sequestered based on 1997 average (kg carbon/ha)	Crop area (million ha)	Total addition carbon sequestered (million kg)	Total addition Carbon dioxide sequestered (million kg)
1997	0.0	6.2	0.00	0.00
1998	10.0	6.1	61.19	224.57
1999	20.0	6.0	120.98	444.00
2000	30.0	6.0	179.52	658.84
2001	40.0	6.8	273.52	1,003.82
2002	50.0	7.5	374.35	1,373.86
2003	60.0	8.2	492.84	1,808.72
2004	70.0	8.6	601.16	2,206.26
2005	80.0	8.3	663.60	2,435.41
2006	90.0	8.2	742.23	2,723.98
2007	90.0	8.2	736.65	2,703.51
2008	100.0	8.2	822.70	3,019.31
2009	106.0	8.9	943.51	3,462.67
2010	110.0	9.1	1,004.69	3,687.19
2011	110.0	9.1	1,001.67	3,676.13
2012	114.0	9.9	1,126.76	4,135.23
2013	120.0	10.5	1,259.12	4,620.99
2014	120.0	11.1	1,328.89	4,877.03
Total			11,733.38	43,061.51

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 (1998–2014)

	Annual reduction based on 1997 average (liters/ha)	Crop area (million ha)	Total fuel saving (million liters)	Carbon dioxide (million kg)
1997	0.00	32.19	0.00	0.00
1998	−0.30	32.44	−9.58	−25.57
1999	−0.14	31.32	−4.43	−11.84
2000	0.01	32.19	0.39	1.03
2001	0.11	30.64	3.30	8.81
2002	0.20	31.93	6.50	17.34
2003	0.31	31.81	10.00	26.71
2004	0.43	32.47	13.82	36.90
2005	0.78	33.10	25.85	69.01
2006	1.14	31.70	36.02	96.18
2007	1.47	37.88	55.82	149.05
2008	1.34	31.82	42.72	114.06
2009	1.98	32.21	63.74	170.18
2010	1.78	32.78	58.20	155.40
2011	1.93	34.35	66.22	176.82
2012	1.93	35.36	68.16	182.00
2013	1.93	35.48	68.39	182.61
2014	1.93	33.64	64.86	173.17
Total			569.99	1,521.87

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

US maize: Potential additional soil carbon sequestration (1998 to 2014)

	Annual increase in carbon sequestered based on 1997 average (kg carbon/ha)	Crop area (million ha)	Additional carbon sequestered (million kg)	Additional Carbon dioxide sequestered (million kg)
1997	0.0	32.2	0.00	0.00
1998	−2.8	32.4	−90.93	−333.70
1999	−1.2	31.3	−36.32	−133.29
2000	0.5	32.2	15.56	57.11
2001	1.5	30.6	44.90	164.78
2002	2.4	31.9	78.15	286.81
2003	3.6	31.8	114.19	419.09
2004	4.7	32.5	153.64	563.84
2005	8.4	33.1	277.58	1,018.73
2006	12.0	31.7	381.73	1,400.94
2007	15.4	37.9	585.14	2,147.48
2008	14.1	31.8	448.24	1,645.05
2009	20.7	32.2	666.49	2,446.01
2010	18.6	32.8	609.91	2,238.37
2011	20.2	34.4	693.29	2,544.38
2012	20.2	35.4	713.60	2,618.91
2013	20.2	35.5	716.00	2,627.71
2014	20.2	33.6	678.98	2,491.87
Total			6,050.16	22,204.08

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 (1996–2014)

	Annual reduction based on 1996 average 30.6 (l/ha)	Crop area (million ha)	Total fuel saving (million liters)	Carbon dioxide (million kg)
1996	0.0	3.5	0.0	0.00
1997	0.9	4.9	4.3	11.51
1998	0.9	5.4	4.8	12.83
1999	0.9	5.6	4.9	13.15
2000	0.9	4.9	4.3	11.48
2001	1.8	3.8	6.7	17.89
2002	2.7	3.3	8.7	23.12
2003	3.5	4.7	16.6	44.32
2004	4.4	4.9	21.9	58.35
2005	5.3	5.5	29.2	77.85
2006	6.2	5.2	32.5	86.64
2007	6.5	5.9	38.7	103.36
2008	7.1	6.5	46.0	122.77
2009	8.0	6.4	50.8	135.59
2010	8.8	6.5	57.7	153.93
2011	8.9	7.5	66.1	176.54
2012	8.9	8.6	76.0	202.86
2013	8.9	7.8	69.1	184.61
2014	8.9	8.3	73.8	197.16
Total			612.0	1,634.0

Notes: fuel usage NT/RT = 17.3 liters/ha CT = 35 liters/ha

Canadian canola: Potential additional soil carbon sequestration (1996 to 2014)

	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
Total			2,247.35	8,247.79

Notes: 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 (1996–2014)

	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 liters)	CO2 emissions saved (million kg)
1996	6.64	0.86	3.45	2.90	7.73
1997	6.35	0.92	3.67	3.09	8.24
1998	7.20	1.05	4.20	3.53	9.43
1999	7.42	2.11	8.44	7.09	18.92
2000	7.29	2.43	9.72	8.17	21.81
2001	7.25	2.55	10.18	8.55	22.84
2002	6.36	2.17	8.69	7.30	19.49
2003	5.34	2.17	8.70	7.30	19.50
2004	6.03	2.79	11.17	9.38	25.05
2005	6.34	3.21	12.84	10.78	28.79
2006	7.90	3.94	15.75	13.23	35.33
2007	6.07	3.25	12.99	10.91	29.14
2008	4.51	2.54	10.16	8.53	22.78
2009	5.33	2.96	11.83	9.94	26.54
2010	7.13	4.59	18.37	15.43	41.21
2011	6.61	4.43	17.71	14.87	39.71
2012	5.72	4.03	16.11	13.53	36.12
2013	5.29	3.75	15.01	12.61	33.66
2014	5.57	4.16	16.64	13.98	37.32
Total			215.63	181.13	483.61

Notes: assumptions: 4 tractor passes per ha, 0.84 liters/ha of fuel per insecticide application.