GM Crops & Food: Biotechnology in Agriculture and the Food Chain 5:2, 149–160; April/May/June 2014; © 2014 Landes Bioscience

Key global environmental impacts of genetically modified (GM) crop use 1996–2012

Peter Barfoot and Graham Brookes*

PG Economics; Dorchester, UK

Keywords: GMO, pesticide, active ingredient, environmental impact quotient, carbon sequestration, biotech crops, no tillage

Against the background of increasing awareness and appreciation of issues such as global warming and the impact of mankind's activities such as agriculture on the global environment, this paper updates previous assessments of some key environmental impacts that crop biotechnology has had on 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. The adoption of the technology has reduced pesticide spraying by 503 million kg (-8.8%) and, as a result, decreased the environmental impact associated with herbicide and insecticide use on these crops (as measured by the indicator the Environmental Impact Quotient [EIQ]) by 18.7%. The technology has also facilitated a significant reduction in the release of greenhouse gas emissions from this cropping area, which, in 2012, was equivalent to removing 11.88 million cars from the roads.

Introduction

GM crop traits have mainly been adopted in four main crops; canola, maize, cotton, and soybean, and in 2012, accounted for 45% 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 also been planted.

The main traits so far commercialized 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 and cotton. 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 (e.g., *Ostrinia nubilalis, Ostrinia furnacalis, Spodoptera frugiperda, Diatraea spp, Helicoverpa zea*, and *Diabrotica spp*) in maize and bollworm and/or budworm (*Heliothis sp and Helicoverpa*) in cotton.

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
- 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[1]]). 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 2012 into the context of earlier developments and updates the findings of earlier analysis presented by the authors in AgbioForum 8 (2&3) 187–196,[2] 9 (3) 1–13,[3] 11 (1), 21–38[4], and 13 (1), 76–94[5] and GM Crops (2011), vol 12, issue 1, 34–49, (2012) 3: 2 April–June 2012, p 1–9, and (2013) 4:2 April–June, p 1–11[6,7,8].

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 analyses because the current paper takes into account the availability of new data and analyses, including revisions to data for earlier years. 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 of this 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

*Correspondence to: Graham Brookes; Email: graham.brookes@binternet.com

Submitted: 08/01/2014; Revised: 04/03/2014; Accepted: 05/03/2014; Published Online: 11/03/2014
http://dx.doi.org/10.4161/gmcr.28449

Table 1. GM HT soybean: summary of active ingredient usage and associated EIQ changes 1996–2012

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	-7.2	-1.0	-10.3
Brazil	+28.4	+3.7	-4.2
USA	-27.6	-3.5	-25.2
Canada	-2.4	-8.3	-22.2
Paraguay	+2.7	+9.4	-6.9
Uruguay	+0.4	+2.4	-9.7
South Africa	+0.2	+3.6	-12.4
Mexico	-0.02	-1.1	-5.4
Bolivia	+0.8	+12.0	-3.6
Aggregate impact: all countries	**-4.74**	**-0.2**	**-15.0**

Notes: Negative sign, reduction in usage or EIQ; positive sign, increase in usage or EIQ value.

more informed decision making, especially in countries where crop biotechnology is currently not permitted.

Results and Discussion

Environmental impacts of insecticide and herbicide use changes

HT crops

The primary impact of GM HT (largely tolerant to glyphosate) technology has been a change in the profile of herbicides used. In general, a fairly broad range of mostly selective (grass weed and broad-leaved weed) herbicides has been replaced by one or two broad-spectrum herbicides (mostly glyphosate) used in conjunction with one or two other (complementary) herbicides (e.g., 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, indicating net improvements to the environment (for an explanation of the EIQ indicator, see the methodology section);
- In some 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, 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 and has become a major problem in some regions (see www.weedscience.org). This can be attributed to how glyphosate was used; because of its broad-spectrum post-emergence activity, it was often used as the sole method of weed control. This approach to weed control put tremendous selection pressure on weeds and as a result contributed to the evolution of weed populations predominated by resistant individual weeds. In addition, the facilitating role of 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 already begun to influence the mix, total amount, cost, and overall profile of herbicides applied to GM HT crops. Compared with five 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. However, relative 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 with the conventional alternative (as measured by the EIQ indicator). 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.

GM HT soybean

The environmental impact of herbicide use change associated with GM HT soybean adoption is summarized in **Table 1**. Overall, there has been a small net decrease in the amount of herbicide active ingredient used (-0.2%), which equates to about 4.7 million kg less active ingredient applied to these crops than would otherwise have occurred if a conventional crop had been planted. The environmental impact, as measured by the EIQ indicator, nevertheless, improved by a more significant 15% due to the increased usage of more environmentally benign herbicides.

Table 2. GM HT maize: summary of active ingredient usage and associated EIQ changes 1996–2012

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
USA	-182.9	-10.6	-14.1
Canada	-8.2	-18.3	-21.1
Argentina	-5.0	-6.7	-9.3
South Africa	-1.1	-1.2	-4.6
Brazil	-6.1	-5.0	-15.8
Aggregate impact: all countries	**-203.2**	**-9.8**	**-13.3**

Notes: (1) Negative sign, reduction in usage or EIQ; positive sign, increase in usage or EIQ value. (2) Other countries using GM HT maize: Colombia and the Philippines, not included due to lack of data. Also, hand weeding is likely to be an important form of weed control suggesting any reduction in herbicide use with GM HT maize has been limited.

Table 3. GM HT cotton summary of active ingredient usage and associated EIQ changes 1996–2012

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
USA	-13.0	-5.3	-7.5
South Africa	+0.01	+1.2	-7.2
Australia	-0.8	-4.4	-4.3
Argentina	-4.5	-32.5	-39.0
Aggregate impact: all countries	**-18.31**	**-6.0**	**-9.0**

Notes: (1) Negative sign, reduction in usage or EIQ; positive sign, increase in usage or EIQ value. (2) Other countries using GM HT cotton: Brazil, Colombia, and Mexico, not included due to lack of data

At the country level, most 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. The exceptions to this have been Brazil, Bolivia, Paraguay, South Africa, and Uruguay, where there have been net increases in the amount of herbicide active ingredient applied, though the overall environmental impact, as measured by the EIQ indicator has been positive. 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 two additional, complementary herbicides targeted at weeds that are difficult to control with glyphosate.

In 2012, the amount of herbicide active ingredient applied to the global GM HT soybean crop increased by 13.2 million kg (+7.4%) 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 2012 GM HT soybean crop continued to represent an improvement relative to the conventional alternative (a 6.9% improvement).

GM HT maize

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

In 2012, the reduction in herbicide usage was just over 20.6 million kg of active ingredient (-11%), with a larger reduction in the EIQ indicator of 22%. As with GM HT soybeans, the greatest environmental gains have been in developed countries (e.g., 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 18.3 million kg over the 1996–2012 period. This represents a 6.6% reduction in usage, although in terms of the EIQ indicator, the change has been a higher 9% reduction (i.e., there has been a net environmental improvement). In 2011, the use of GM HT cotton technology resulted in a 2.7 million kg reduction in herbicide active ingredient use (-13.3%) and an 18.5% reduction in the field EIQ indicator value (**Table 3**).

Other HT crops

GM HT canola (tolerant to glyphosate or glufosinate) has been grown in Canada, the US, and more recently Australia, while GM HT sugar beet is grown in the US and Canada. The environmental impacts associated with changes in herbicide usage on these crops are summarized in **Table 4**. GM HT canola use has resulted in significant reductions in both the amount of herbicide active ingredient used and the associated field EIQ indicator.

In respect of GM HT sugar beet, the change in herbicide usage away from several selective herbicides to a fewer applications of, often a single herbicide (glyphosate) has resulted in an increase in the total volume of herbicides applied to the sugar beet crop, but

Table 4. Other GM HT crops summary of active ingredient usage and associated EIQ changes 1996–2012

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
GM HT canola			
US	-2.7	-34.5	-46.5
Canada	-12.1	-17.2	-27.2
Australia	-0.2	-1.8	-1.1
Aggregate impact: all countries	**-15.0**	**-16.7**	**26.6**
GM HT sugar beet			
US and Canada	+1.3	+29.3	-2.0

Notes: (1) Negative sign, reduction in usage or EIQ; positive sign, increase in usage or 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's hybrid vigour canola (tolerant to the herbicide glufosinate) is higher yielding than conventional or other GM HT canola and derives this additional vigour from GM techniques. (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.

a small net improvement in the associated environmental impact (-2%).

In 2012, the use of GM HT canola resulted in a 2.0 million kg reduction in the amount of herbicide active ingredient use (-14.9%), with an improvement in the environmental impact, as measured by the EIQ indicator of 33.9%. For GM HT sugar beet, an additional 0.43 million kg of herbicide active ingredient was applied to the sugar beet crops in the US and Canada (+55%). This also resulted in a small net deterioration in the associated environmental impact (-8%: 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 2014) 28 weeds species resistant to glyphosate of which several are not associated with glyphosate tolerant crops (www.weedscience.org). In the US, there are currently 14 weeds recognized as exhibiting resistance to glyphosate, of which two are not associated with glyphosate tolerant crops. In Argentina, Brazil and Canada, where GM HT crops are widely grown, the number of weed species exhibiting resistance to glyphosate are respectively 7, 5, and 4. A few of the glyphosate-resistant species, such as marestail (*Conyza canadensis*), waterhemp (*Amaranthus tunberculatus*), and palmer pigweed (*Amaranthus palmeri*) in the US, are now reasonably widespread, with the affected area being possibly within a range of 20–40% 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, 135 weed species that are resistant to ALS herbicides and 72 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 minimize and slow down the potential for weeds developing resistance to existing technology solutions for their control. At the macro level, these changes have already begun to influence the mix, total amount, cost, and overall profile of herbicides applied to GM HT crops.

For example, in the 2012 US GM HT soybean crop, 59% of the GM HT soybean crop received an additional herbicide treatment of one of the following (four most used, after glyphosate) active ingredients 2,4-D (used pre crop planting), chlorimuron, flumioxazin and fomesafen (each used primarily after crop planting). This compares with 14% of the GM HT soybean crop receiving a treatment of one of these four 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 55% 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 program and not to rely on a single herbicide mode of action for total weed management. It is interesting to note that in 2012, glyphosate accounted for about the same share of total active ingredient use on the GM HT crop (about 80%) as in 1998, highlighting that farmers continue to realize value in using glyphosate because of its broad spectrum activity in addition to using other herbicides. On the small conventional crop, the average amount of herbicide active ingredient applied increased by 78% over the same period reflecting a shift in herbicides used rather than increased dose rates for some herbicides. The increase in the use of herbicides on the conventional soybean crop in the US can also be partly attributed to the on-going development of weed resistance to non-glyphosate herbicides commonly used and highlights that the development of weed resistance to herbicides is a problem

Table 5. GM IR maize: summary of active ingredient usage and associated EIQ changes 1996–2012

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
USA	-45.4	-43.7	-38.4
Canada	-0.6	-88.9	-77.3
Spain	-0.5	-34.8	-19.8
South Africa	-1.2	-60.2	-60.2
Brazil	-9.9	-81.0	-81.0
Colombia	-0.1	-56.0	-56.0
Aggregate impact: all countries	**-57.7**	**-47.9**	**-45.1**

Notes: (1) Negative sign, reduction in usage or EIQ; positive sign, increase in usage or EIQ value. (2) Other countries using GM IR maize: Argentina, Uruguay, 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.

Table 6. GM IR cotton: summary of active ingredient usage and associated EIQ changes 1996–2012

Country	Change in active ingredient use (million kg)	% change in amount of active ingredient used	% change in EIQ indicator
USA	-12.2	-17.5	-16.6
China	-112.2	-30.1	-30.9
Australia	-17.3	-32.7	-32.3
India	-61.0	-21.6	-27.2
Mexico	-1.2	-10.1	-10.8
Argentina	-0.9	-16.1	-22.8
Brazil	-0.6	-9.0	-12.3
Aggregate impact: all countries	**-205.4**	**-25.6**	**-28.2**

Notes: (1) Negative sign, reduction in usage or EIQ; positive sign, increase in usage or EIQ value. (2) Other countries using GM IR cotton: Colombia, Burkina Faso, Pakistan and Burma 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.

faced by all farmers, regardless of production method. It is also interesting to note that, since the mid-2000s, the average amount of herbicide active ingredient used on GM HT cotton in the US has increased through a combination of additional usage of glyphosate (about a 30% increase in usage per hectare) in conjunction with increasing use of other herbicides. All of the GM HT crop area planted to seed tolerant to glyphosate received treatments of glyphosate and at least one of the next five most used herbicides (2 4-D [pre-plant] and in-crop applications of flumoxazin, fomesafen, pendimethalin, and diuron). This compares with 2006, when only three-quarters of the glyphosate tolerant crop received at least one treatment from the next five most used herbicides (2 4-D, trifluralin, pyrithiobic, pendimethalin, and diuron). In other words, a quarter of the glyphosate tolerant crop used only glyphosate for weed control in 2006 compared with none of the crop relying solely on glyphosate in 2012. This suggests that US cotton farmers are increasingly adopting current and/or 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 with the conventional alternative (as measured by the EIQ indicator).

GM IR crops

The main way in which these technologies have impacted on the environment has been through reduced insecticide use (**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 regimens of insecticides were common place to control bollworm and/or 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 and/or bollworm pests are in cotton. In addition, insecticides were widely considered to have limited effectiveness against some pests in maize crops (e.g., stalk borers) because the pests can be found in places where sprays are not effective (e.g., 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

Table 7. Carbon storage/sequestration from reduced fuel use with GM crops 2012

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	79	210	93
Argentina: GM HT soybean	275	736	321
Brazil GM HR soybean	148	394	175
Bolivia, Paraguay, Uruguay: GM HT soybean	58	156	69
US: GM HT maize	79	210	93
Canada: GM HT canola	76	203	90
Global GM IR cotton	17	45	20
Brazil IR maize	59	157	69
Total	***791***	***2111***	***930***

Notes: (1) Assumption: an average family car produces 150 g of carbon dioxide per km. A car does an average of 15 000 km per year and therefore produces 2,250 kg of carbon dioxide per year. (2) GM IR cotton. Burkina Faso, India, Pakistan, Burma and China excluded because insecticides assumed to be applied by hand, using back pack sprayers

receiving insecticide treatments (e.g., 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 2012 were, 7.6 million kg (-86.5% of insecticides typically targeted at maize stalk boring and rootworm pests) and 16.8 million kg (-40% of all insecticides used on cotton) respectively of active ingredient use. In EIQ indictor terms, the respective savings in 2012 were 86% for insecticides targeted at maize stalk boring and rootworm pests and 45% for total cotton insecticides. Cumulatively since 1996, the gains have been a 58 million kg reduction in maize insecticide active ingredient use and a 205 million kg reduction in cotton insecticide active ingredient use.

Aggregated (global level) impacts

At the global level, GM technology has contributed to a significant reduction in the 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 was reduced by 503 million kg of active ingredient (an 8.8% reduction), and the environmental impact associated with herbicide and insecticide use on these crops, as measured by the EIQ indicator, fell by 18.8%. In 2012, the environmental benefit was equal to a reduction of 37.5 million kg of pesticide active ingredient use (-8.3%), with the environmental impact associated with insecticide and herbicide use on these crops, as measured by the EIQ indicator, falling by 23.6%.

At the country level, US farms have seen the largest environmental benefits, with a 282 million kg reduction in pesticide active ingredient use (56% of the total). This is not surprising given that US farmers were first to make widespread use of GM crop technology, and for several years, the GM adoption levels in all four US crops have been in excess of 80%, and insecticide and/or 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 173 million kg (1996–2012).

Greenhouse gas emission savings

Reduced fuel use

The fuel savings associated with making fewer spray runs in GM IR crops of maize and cotton (relative to conventional crops) and the switch 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 2012, this amounted to a saving of about 2111 million kg of carbon dioxide, arising from reduced fuel use of 791 million liters (**Table** 7). These savings are equivalent to taking 0.94 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 (71% of total savings). These savings have been greatest in South America.

Over the period 1996 to 2012, the cumulative permanent reduction in fuel use has been about 16 736 million kg of carbon dioxide, arising from reduced fuel use of 6268 million liters. In terms of car equivalents, this is equal to taking nearly 7.44 million cars off the road for a year.

Additional soil carbon storage and/or sequestration

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

Based on savings arising from the rapid adoption of RT/NT farming systems in North and South America, an extra 6707 million kg of soil carbon is estimated to have been sequestered in 2012 (equivalent to 24 613 million tonnes of carbon dioxide that has not been released into the global atmosphere). These savings

Table 8. Context of carbon sequestration impact 2012: 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	292	1070	475
Argentina: GM HT soybean	3048	11 186	4972
Brazil GM HR soybean	1631	5985	2660
Bolivia, Paraguay, Uruguay: GM HT soybean	644	2365	1051
US: GM HT maize	813	2983	1326
Canada: GM HT canola	279	1024	455
Global GM IR cotton	0	0	0
Brazil IR maize	0	0	0
Total	***6707***	***24 613***	***10 939***

are equivalent to taking 10.9 million cars off the road for one year (**Table 8**).

The additional amount of soil carbon sequestered since 1996 has been equivalent to 203 560 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 3-fold 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 (e.g., less soil erosion, greater water retention, and reduced levels of nutrient run off). However, it is equally likely that the total cumulative soil sequestration gains have been lower because only a proportion of the crop area will have remained in NT/RT.

It is, nevertheless, not possible to confidently estimate cumulative soil sequestration gains that take into account reversions to conventional tillage because of a lack of data. Consequently, the estimate provided of 203 560 million tons 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 2012 are equal to about 26 724 million kg, equivalent to taking 11.9 million cars off the road for a year. This is roughly equal to 41% of registered cars in the UK.

Conclusions

During the past 17 years, the adoption of crop biotechnology by many farmers (17.3 million in 2012) 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. Second, the technology has facilitated changes in farming systems by enabling farmers to capitalize 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 are increasingly adopting a mix of reactive and proactive weed management strategies incorporating a mix of herbicides and some of the original environmental gains associated with changes in herbicide use with GM HT crops have therefore diminished. Despite this, the adoption of GM HT crop technology continues to deliver a net environmental gain and, together with GM IR technology, continues to provide substantial net environmental benefits.

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 much more limited than the literature examining the economic impacts associated with use of the technology. Therefore, while this analysis draws on the available literature, it includes 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 some farmers to address issues of weed resistance to the main herbicide (glyphosate) used with GM HT crops.

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 vs. 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[9, 10,11] with even fewer[12,13], providing data to the pesticide (active ingredient) level. Second, national level pesticide usage survey data are 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 are 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 (e.g., the last time maize was included was 2010 and previous to this, in 2005) and do not disaggregate usage by production type (GM vs. conventional).

Even where national pesticide use survey data are 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 and/or insecticides might reasonably be expected to be used in the absence of crop biotechnology on the relevant crops (i.e., 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 estimates of what usage might reasonably be in the absence of crop biotechnology, because the conventional cropping data set 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 2012, the conventional share (not using GM HT technology) of each crop was only 7%, 12%, 6%, and 3% respectively for soybean, maize, cotton and canola, with the conventional share having been below 50% of the total since 1999 in respect of the soybean crop, since 2001 for the cotton and canola crops, and since 2007 for the maize crop (source: USDA—note the conventional 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 herbicide and/or insecticide use that might reasonably be expected in the absence of biotechnology include:

- While the degree of pest and/or weed problems and/or damage vary by year, region, and within region, farmers who continue to farm conventionally may be those with relatively low levels of pest and/or weed problems and hence see little, if any, economic benefit from using the GM traits targeted at minimal pest and/or weed problems. In addition, late or non-adopters of new technology in agriculture are typically those who generally make less use of newer technologies than earlier adopters. As a result, insecticide and/or 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 and/or weed infestations and where farmers are more willing to adopt new technology;
- Some of the farms continuing to use conventional seed generally use extensive, low intensity production methods (including organic), which feature limited (below average) use of herbicides and/or insecticides. The usage patterns of this sub-set of growers is therefore likely to understate usage for the majority of farmers if they all returned to farming without the use of GM technology;
- The widespread adoption of GM IR technology has resulted in "area-wide" suppression of target pests in maize crops. As a result, conventional farmers (e.g., of maize in the US) have benefited from this lower level of pest infestation and the associated reduced need to conduct insecticide treatments;[14]
- Some of the farmers using GM traits have experienced improvements in pest and/or weed control from using this technology relative to the conventional control methods previously used. If these farmers were to now switch back to using conventional techniques, it is likely that most would wish to maintain the levels of pest and/or weed control delivered with use of the GM traits and therefore some would use higher levels of insecticide and/or herbicide than they did in the pre GM crop days. This argument can, however, be countered by the constraining influence on farm level pesticide usage that comes from the cost of pesticides and their application. Ultimately the decision to use more pesticide or not would be made at the farm level according to individual assessment of the potential benefits (from higher yields) compared with the cost of additional pesticide use.

This problem of poor representativeness of the small conventional data set has been addressed by first, using the average recorded values for insecticide and/or herbicide usage on conventional crops for years only when the conventional crop accounted for the majority of the total crop and, second, in other years (e.g., 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 and/or 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 to minimize the scope for overstating likely usage levels on the conventional alternative. Overall, this approach has been applied in other countries where pesticide usage data are available, though more commonly, because of the paucity of available data, the analysis relies more on extension and/or advisor opinion and knowledge of actual and potential pesticide use.

This methodology has been used by others.[15-17] 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 2012 calculations, sources used for each trait and/or country combination examined and examples of typical conventional vs. GM pesticide applications are provided in **Supplemental 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[18]) 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 (e.g., a hypothetical example of 1.1 kg applied per ha), the field EIQ value for glyphosate would be equivalent to 16.86 per ha. The EIQ indicator used is therefore a comparison of the field EIQ per 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 per ha values and the area planted to each type of production (GM vs. conventional). The use of environmental indicators is commonly used by researchers and the EIQ indicator has been, for example, cited by Brimner et al.[19] (2004) in a study comparing the environmental impacts of GM and conventional canola and by Kleiter et al.[20] (2005). The EIQ indicator provides an improved assessment of the impact of GM crops on the environment when compared with 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.

In this paper, the EIQ indicator is used in conjunction with examining changes in the volume of pesticide active ingredient applied. Readers should, however, note that the EIQ is an indicator of environmental toxicity only and does not take into account all environmental issues and impacts (e.g., impacts on soil erosion). It is therefore not a comprehensive indicator.

Detailed examples of the relevant amounts of active ingredient used and their associated field EIQ values for GM vs. conventional crops for the year 2012 are presented in **Supplemental Appendix 2**.

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.[21-29]

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 L per ha (Lazarus [2012][30]). In terms of GHG, each liter of tractor diesel consumed contributes an estimated 2.67 kg of carbon dioxide into the atmosphere (this also updates a previously used co-efficient of 2.75 to convert 1 L of diesel to kg of carbon dioxide). 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 and/or 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][21] and American Soybean Association [2001][22]), especially where soybean growing and/or a soybean: corn rotation are commonplace. Before the introduction of GM HT technology, RT/NT systems were practiced 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 2012, RT/NT production accounted for 80% 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 2012, accounted for 75% of the total crop (95% 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,[24] CTIC[21,] University of Illinois,[31] USDA Energy Estimator,[32] Reeder,[33] and the USDA Comet-VR model.[34] 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 L/ha compared with traditional conventional tillage and in the case of RT (mulch till) cultivation by 10.39 L/ha. In the case of maize, NT results in a saving of 24.41 L/ha and 7.52 L/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.

Second, 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.[1,26-28,35-43] 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 systems.

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.[44]

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

US: In previous editions of this report no differentiation was made between corn and soybeans and the assumptions used were based on a difference between NT and CT of 400 kg of carbon/ha per year of soil carbon sequestered (NT systems store 375 kg of carbon/ha per year; RT systems store 175 kg of carbon/ha per year; and CT systems store 25 kg of carbon/ha per year). In this report, 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 per year based on:

- NT systems store 251 kg of carbon/ha per year;
- RT systems store 75 kg of carbon/ha per year;
- CT systems store 1 kg of carbon/ha per 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 per year based on:

- NT systems release 45 kg of carbon/ha per year;
- RT systems release 115 kg of carbon/ha per year;
- CT systems release 145 kg of carbon/ha per year.[45-56]

Argentina and Brazil: soil carbon retention is 275 kg carbon/ha per year for NT soybean cropping and CT systems release 25 kg carbon/ha per year (a difference of 300 kg carbon/ha per year). In previous editions of this report the difference used was 200 kg carbon/ha per 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 utilized 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 (i.e., parts of Brazil).[57-66]

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

Disclosure of Potential Conflicts of Interest

The authors acknowledge that funding toward the researching of this paper was provided by Monsanto. The material presented in this paper is, however, the independent views of the authors; it is a standard condition for all work undertaken by PG Economics that all reports are independently and objectively compiled without influence from funding sponsors.

Supplemental Materials

Supplemental materials may be found here:
www.landesbioscience.com/journals/gmcrops/article/28449

References

1. 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.
2. Brookes G, Barfoot P. Global impact of biotech crops: socio-economic and environmental effects 1996-2004. AgbioForum 2006; 8:187-96
3. Brookes G, Barfoot P. Global impact of biotech crops: socio-economic and environmental effects 1996-2005. Agbioforum 2007; 9L:1-13
4. Brookes G, Barfoot P. Global impact of biotech crops: socio-economic and environmental effects 1996-2006. Agbioforum 2008; 11:21-38
5. Brookes G, Barfoot P. Global impact of biotech crops: environmental effects 1996-2008. AgBioforum 2010; 13:76-94
6. Brookes G, Barfoot P. Global impact of biotech crops: environmental effects 1996-2009. GM Crops 2011; 2:34-49; PMID:21844697; http://dx.doi.org/10.4161/gmcr.2.1.15529
7. Brookes G, Barfoot P. Global impact of biotech crops: environmental effects, 1996-2010. GM Crops Food 2012; 3:129-37; PMID:22534352; http://dx.doi.org/10.4161/gmcr.20061
8. Brookes G, Barfoot P. Key environmental impacts of global GM crop use 1996-2011. GM Crops 2013; 4:1-11; PMID:23635915
9. 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
10. Qaim M. Traxler G Roundup Ready soybeans in Argentina: farm level, environmental and welfare effects, 6th ICABR conference. 2002. Ravello, Italy.
11. Pray CE, Huang J, Hu R, Rozelle S. Five years of Bt cotton in China - the benefits continue. Plant J 2002; 31:423-30; PMID:12182701; http://dx.doi.org/10.1046/j.1365-313X.2002.01401.x
12. 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.
13. Brookes G. The farm-level impact of herbicide-tolerant soybeans in Romania. AgBioForum 2005; 8:235-41
14. Hutchison WD, Burkness EC, Mitchell PD, Moon RD, Leslie TW, Fleischer SJ, Abrahamson M, Hamilton KL, Steffey KL, Gray ME, et al. Areawide suppression of European corn borer with Bt maize reaps savings to non-Bt maize growers. Science 2010; 330:222-5; PMID:20929774; http://dx.doi.org/10.1126/science.1190242
15. 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.
16. 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.
17. 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.
18. 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.
19. Brimner TA, Gallivan GJ, Stephenson GR. Influence of herbicide-resistant canola on the environmental impact of weed management. Pest Manag Sci 2005; 61:47-52; PMID:15593073; http://dx.doi.org/10.1002/ps.967
20. 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.
21. Conservation Tillage and Plant Biotechnology (CTIC). How new technologies can improve the environment by reducing the need to plough. 2002.
22. American Soybean Association Conservation Tillage Study. 2001.
23. Fabrizzi K, Moron A, Garan F. Soil Carbon and Nitrogen Organic Fractions in Degraded VS Non-Degraded Mollisols in Argentina. Soil Sci Soc Am J 2003; 67:1831-41; http://dx.doi.org/10.2136/sssaj2003.1831
24. Jasa P. Conservation Tillage Systems, Extension Engineer, University of Nebraska. 2002.
25. Reicosky D. Conservation tillage and carbon cycling: soil as a source or sink for carbon. University of Davis, USA. 1995.
26. Robertson GP, Paul EA, Harwood RR. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 2000; 289:1922-5; PMID:10988070; http://dx.doi.org/10.1126/science.289.5486.1922
27. Johnson, et al. Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil Tillage Res 2005; 83:73-94; http://dx.doi.org/10.1016/j.still.2005.02.010
28. Leibig, et al. Greenhouse gas contributions and mitigation potential of agriculture practices in north-western USA and Western Canada. Soil Tillage Res 2005; 83:25-52; http://dx.doi.org/10.1016/j.still.2005.02.008
29. West T, Post W. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Analysis. Soil Sci Soc Am J 2002; 66:930-1046; http://dx.doi.org/10.2136/sssaj2002.1930
30. Lazarus W F. Machinery Cost Estimates May 2012, University of Minnesota Extension Service.
31. Costs and fuel use for alternative tillage systems [Internet]. Urbana-Champaign (IL); University of Illinois: c2006 [cited 2014 Jan 8]. Available on the World Wide Web: http;//www.farmdoc.uiuc.edu/manage/newsletters/fefo06 07/fefo06 07.html
32. Energy Estimator USDA. tillage [Internet]. Washington, DC; United States Department of Agriculture: c2006 [cited 2014 Jan 8]. Available from: http://ecat.sc.egov.usda.gov
33. Reeder R. No-till benefits add up with diesel fuel savings [Internet]. Mankato (MN): The Land; c2010 [cited 2014 Jan 8]. Available from: http://www.thelandonline.com/currentedition/x1897235554/No-till-benefits-add-up-with-diesel-fuel-savings
34. An online tool for estimating carbon storage in agroforestry practices [Internet]. Washington, DC: USDA Comet-VR: c2013 [cited 2014 Jan 8]. Available from: www.cometvr.colostate.edu
35. Calegari A, et al. Impact of Long-Term No-Tillage and Cropping System Management on Soil Organic Carbon in an Oxisil: A Model for Sustainability. Agron J 2002; 100:1013-9; http://dx.doi.org/10.2134/agronj2007.0121
36. Baker JM, Ochsner TE, Venterea RT, Griffis TJ. Tillage and soil carbon sequestration—What do we really know? Agric Ecosyst Environ 2007; 118:1-5; http://dx.doi.org/10.1016/j.agee.2006.05.014
37. 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
38. 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
39. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science 2004; 304:1623-7; PMID:15192216; http://dx.doi.org/10.1126/science.1097396
40. Lal R. Enhancing Crop Yields in the Developing Countries through Restoration of the Soil Organic Carbon Pool in Agricultural Lands. Land Degrad Dev 2005; 17:197-209; http://dx.doi.org/10.1002/ldr.696
41. Lal R. Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food Security 2010; 2:169-77; http://dx.doi.org/10.1007/s12571-010-0060-9
42. Bernacchi, et al. The conversion of the corn/soybean ecosystem to no-till agriculture may result in a carbon sink. Glob Change Biol 2005; 11:1867-72
43. Michegan State University. US Cropland greenhouse gas calculator. 2013. http://surfkbs.msu.edu
44. Wutzler T, Reichstein M. Soils apart from equilibrium – consequences for soil carbon balance modelling. Biogeosciences Discuss 2006; 3:1679-714; http://dx.doi.org/10.5194/bgd-3-1679-2006
45. Gianessi L, Carpenter J. Agricultural biotechnology: Insect control benefits. Washington, DC: NCFAP. 1999.
46. Monsanto Brazil. Farm survey of conventional and Bt cotton growers in Brazil 2007 (unpublished). 2008.
47. Galveo A. Farm survey findings of impact of insect resistant cotton in Brazil, Celeres, Brazil. 2009 & 2010.
48. Galveo A. Farm survey findings of impact of GM crops in Brazil 2011, Celeres, Brazil (2012).
49. George Morris Centre. Economic & environmental impacts of the commercial cultivation of glyphosate tolerant soybeans in Ontario (unpublished report). Guelph, Ontario: Author. 2004.

50. 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
51. Gusta M, et al. Changes in chemical toxicity following adoption of herbicide tolerant canola in Western Canada, University of Saskatchewan. 2009. College of Biotechnology Working Paper.
52. 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.
53. 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.
54. Doyle B. The performance of roundup ready cotton 2001-2002 in the Australian cotton sector. Armidale, Australia: University of New England. 2003.
55. Commonwealth Scientific and Industrial Research Organisation (CSIRO). The cotton consultants Australia 2005 Bollgard II comparison report. Collingwood, Australia. 2005.
56. 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.
57. Brookes G. The benefits of adopting GM insect resistant (Bt) maize in the EU: First results from 1998-2006. Int J Biotechnol 2008; 134:3-4
58. Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2011 cotton crop, unpublished. 2012.
59. Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2009 cotton crop, unpublished. 2009.
60. Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2008 cotton crop, unpublished. 2008.
61. Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2007 cotton crop, unpublished. 2007.
62. Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2005 cotton crop, unpublished. 2005.
63. 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.
64. Asia-Pacific Consortium on Agricultural Biotechnology (APCoAB). Bt cotton in India: a status report, ICRASTAT, New Delhi, India. 2006.
65. IMRB International. Socio-economic benefits of Bollgard and product satisfaction (in India). Mumbai, India: Author. 2006.
66. IMRB International. Socio-economic benefits of Bollgard and product satisfaction in India. Mumbai, India: Author. 2007.