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

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

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, Heliothis zea, and Diabrotica spp) in maize and bollworm and/or budworm (Helicoverpa z 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]). 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, 9 (3) 1–13, 11 (1), 21–38, and 13 (1), 76–94 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. 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...
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 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                                        | -10.1                     |
| Brazil           | +28.4                                       | +3.7                                        | -4.2                      |
| USA              | -7.6                                        | -3.5                                        | -25.2                     |
| Canada           | -3.4                                        | -8.3                                        | -22.2                     |
| Paraguay         | +2.7                                        | +9.6                                        | -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.
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| -0.0                                       | -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.

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 EQI 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.
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 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 imidazolinone 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 (tolypophosphate) canola has occurred. (3) Inflor’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.
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 insecticide treatments before the availability of GM IR technology. 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 [pre-plant] and in-crop applications of flumioxazin, fomesafen, pendimethalin, and diuron). This is particularly evident in respect of crops. This is particularly evident in respect of

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 pest species. 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 saved 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 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 budworm 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
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 EQI indicator 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 EQI indicator, fell by 18.9%. 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 EQI 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 16736 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 24.63 million tonnes of carbon dioxide that has not been released into the global atmosphere). These savings

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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                          | 263                                                                                           | 90                                                                                             |
| Global GM IR cotton   | 17                          | 45                                                                                           | 20                                                                                             |
| Brazil IR maize      | 59                          | 157                                                                                           | 69                                                                                             |
| **Total**            | **791**                     | **2111**                                                                                      | **930**                                                                                        |
The additional amount of soil carbon sequestered since 1996 has been equivalent to 203.56 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 203.56 million tonnes 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

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   | 202                                                  | 475                                                                             | 4972                                                                                         |
| Argentina: GM HT soybean | 3048                                                | 11186                                                                           | 4972                                                                                         |
| Brazil GM RR soybean | 1631                                                | 5985                                                                            | 2660                                                                                         |
| Bolivia, Paraguay, Uruguay: GM HT soybean | 644                                                 | 2365                                                                            | 1051                                                                                         |
| US.-GM HT maize     | 813                                                 | 2981                                                                            | 1326                                                                                         |
| Canada: GM HT canola | 279                                                 | 1024                                                                            | 455                                                                                          |
| Global-GM IR cotton | 0                                                   | 0                                                                               | 0                                                                                             |
| Brazil IR maize     | 0                                                   | 0                                                                               | 0                                                                                             |
| Total               | 6707                                                | 24613                                                                           | 10939                                                                                        |

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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" forms 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 changes with GM crops shows that the number of studies exploring these issues is limited\(^9\) \(^10\) \(^11\) with even fewer\(^12\) \(^13\) \(^14\), providing data to the with GM crops shows that the number of studies exploring these issues is limited\(^9\) \(^10\) \(^11\) with even fewer\(^12\) \(^13\) \(^14\), providing data to the

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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 or understating 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 data, the methodology has been applied to the 2012 calculations, sources for each trait and/or country combination examined and 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 diazinon 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. For example, 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 15.35. 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 Brunnier et al. (2004) 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 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 used and/or advisor opinion and knowledge of actual and potential pesticide use. This methodology has been used by others. It also has the advantage of providing comparisons of current crop protection practices on both GM crops and the conventional alternatives and so takes into account dynamic changes in crop protection 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 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

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]). 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 underestimate 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] 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 40% 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,31 University of Illinois,32 USDA Energy Estimator,33 Reeder,34 and the USDA Comet-VR model.35 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 studied or sequestered in the soil and therefore reduces carbon dioxide emissions to the environment. A number of researchers have estimated the amount of 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 25 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 145 kg of carbon/ha per year.
- RT systems release 115 kg of carbon/ha per year;
- CT systems release 45 kg of carbon/ha per year.

The temporary nature of this form of carbon storage only becomes permanent when farmers adopt a continuous RT/NT system and 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 in equilibrium 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.

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 100 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 25 kg of 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).

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, and 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/gm crops/article/28649
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