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Global Impact of Biotech Crops: Socio-Economic and Environmental Effects in the First Ten Years of Commercial Use

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Genetically modified (GM) crops have now been grown commercially on a substantial scale for ten years. This paper assesses the impact this technology is having on global agriculture from both economic and environmental perspectives. It examines specific global economic impacts on farm income and environmental impacts of the technology with respect to pesticide usage and greenhouse gas emissions for each of the countries where GM crops have been grown since 1996. The analysis shows that there have been substantial net economic benefits at the farm level amounting to $5 billion in 2005 and $27 billion for the ten year period. The technology has reduced pesticide spraying by 224 million kg (equivalent to about 40% of the annual volume of pesticide active ingredient applied to arable crops in the European Union) and as a result, decreased the environmental impact associated with pesticide use by more than 15%. GM technology has also significantly reduced the release of greenhouse gas emissions from agriculture, which, in 2005, was equivalent to removing 4 million cars from the roads.

Key words: Yield, cost, income, environmental impact quotient, carbon sequestration, GM crops.

Introduction

This study presents the findings of research into the global economic and environmental impact of genetically modified (GM) crops since their commercial introduction in 1996 and updates the findings of earlier analysis presented by the authors in AgBioForum 8(2&3).[1]

The economic impact analysis concentrates on farm income effects because this is a primary driver of adoption amongst farmers (both large commercial and small-scale subsistence) and is an area for which much analysis has been undertaken. The environmental impact analysis focuses on changes in the use of insecticides and herbicides with GM crops and the resulting environmental impact from crop production. Lastly, the analysis examines the contribution of GM crops towards reducing global greenhouse gas (GHG) emissions resulting from reduced tractor fuel consumption and additional soil sequestration (storage) associated with reduced- or no-tillage cultivation facilitated by the application of GM herbicide-tolerant (HT) technology.

1. *Readers should note that some data presented in this paper are not directly comparable with data presented in the AgBio-Forum 8(2&3) paper because the current paper takes into account the availability of new data and analysis (including revisions to data applicable to earlier years).*

Methodology

The report has been compiled based largely on an extensive analysis of existing farm-level impact data from GM crops. Primary data for impacts of commercial cultivation were not available for every crop, in every year, and for each country. However, all representative, previous research that was identified has been utilized. The findings of this research have been used as the basis for the analysis presented,[2] although where relevant, primary analysis has been undertaken from base data, most notably in relation to the environmental impacts.

The analysis presented is largely based on the average performance and impact recorded in different crops. The economic performance and environmental impact of the technology at the farm level varies widely, both between and within regions/countries. As a result, the impact of this technology, and any new technology (GM or otherwise) is subject to variation at the local level. Thus the performance and impact should be considered on a case-by-case basis in terms of crop and trait combinations.

Agricultural production systems are dynamic and vary with time. This analysis seeks to address this issue,

2. *Where several pieces of research of relevance to one subject (e.g., the impact of using a GM trait on the yield of a crop) have been identified, the findings used have been largely based on the most conservative finding.*

wherever possible, by comparing GM production systems with the most likely conventional alternative that could provide competitive levels of efficacy, if GM technology had not been available. This approach has been used by other researchers (e.g., Sankula & Blumenthal, 2003, 2005).

Farm income effects

Methodology

The methodology for assessing the farm-level impact has been to review existing literature from as many years of relevant comparable data as possible and to use the findings as the basis for the impact estimates over the ten-year period examined. All values presented are nominal for the year shown and actual average prices and yields are used for each year. The base currency used is the US dollar and all financial impacts in other currencies have been converted to US dollars at prevailing annual average exchange rates for each year. The approach reflects changes in farm income in each year arising from the impact of GM technology on yields, key costs of production (notably seed cost and crop protection expenditure, but also impact on costs such as fuel and labor),[3] crop quality, and the scope for facilitating the planting of a second crop in a season. Through the inclusion of yield impacts and taking price changes into account, the analysis also takes into account the possible impact of GM crop adoption on global crop supply and world prices.

Clearly, this simplistic approach may overstate or understate the real impact of GM technology and therefore the authors acknowledge that this represents a weakness of the research. However, the use of current prices does incorporate into the analysis some degree of dynamic that would otherwise be missing if constant prices had been used. Where yield impacts have been identified for specific years, these have been used. Hence, the analysis takes into account variation in the impact of the technology on yield according to its effectiveness in dealing with (annual) fluctuations in pest and weed infestation levels.[4] Nevertheless, much of the literature reviewed has analyzed one or a limited number of years. Where analysis is this limited, the impacts identified have been converted into a percentage change impact and applied to all other years on the basis of the prevailing average yield recorded. For example, if a study identified a yield gain of 5% in year one, this 5% yield increase was then applied to the average yield recorded in each other year. If more than one study identified differing levels of yield impact, the more conservative yield impacts have been used (e.g., in relation to the impact of GM insect-resistant (IR) cotton in the US, analysis by Sankula and Blumenthal (2003) put the average positive yield impact of Bollgard I at +9% while the average yield impact based on Marra, Pardey, and Alston (2002) is +11%; the yield impact used in this paper was +9%).[5]

Farm level impacts

Results

GM technology has had a very positive impact on farm income derived from a combination of enhanced productivity and efficiency gains (Table 1). In 2005, the direct global farm income benefit from GM crops was $5 billion. If the additional income arising from second crop soybeans in Argentina is considered, this income gain rises to $5.6 billion. This is equivalent to having added between 3.6% and 4.0% to the value of global production of the four main crops of soybeans, maize, canola, and cotton, which is a substantial impact. Since 1996, farm incomes have increased by $24.2 billion, or $27 billion inclusive of second crop soybean gains in Argentina.

The largest gains in farm income have arisen in the soybean sector, largely from cost savings, where the $2.84 billion additional income generated by GM HT soybeans in 2005 has been equivalent to adding 7.1% to the value of the crop in the GM growing countries, or

3. *Inclusion of impact on these categories of cost are, however, more limited than the impacts on seed and crop protection costs because only a few authors reviewed have included consideration of such costs in their analysis.*

4. *Examples where such data is available include the impact of Bt cotton in India (see Bennett et al., 2004; APCoAB, 2006), in Mexico (see Traxler et al., 2001; Monsanto Comercial Mexico, 2004) and in the US (see Sankala & Blumenthal, 2003, 2005; Mullins & Hudson, 2004).*

5. *The average base yield has been adjusted downward (if necessary) to account for any positive yield impact of the technology. In this way the impact on total production of any yield gains is not overstated. The authors do, however, acknowledge that the use of this assumption may still over- or understate the yield effects in some years because yield impact findings from a limited number of years have been used as the basis for estimating impact in other years. However, in the absence of comprehensive yield impact analysis for each trait, country and year, the authors consider this an appropriate approach to take in order to estimate cumulative impact.*

Table 1. Global farm income benefits from growing GM crops 1996-2005 (million US $).

Trait	Increase in farm income 2005	Increase in farm income 1996-2005	Farm income benefit in 2005 as % of total value of production of these crops in GM adopting countries	Farm income benefit in 2005 as % of total value of global production of these crops
GM HT soybeans	2,281 [2,842]	11,686 [14,417]	5.72 [7.1]	4.86 [6.05]
GM HT maize	212	795	0.82	0.39
GM HT cotton	166	927	1.16	0.64
GM HT canola	195	893	9.45	1.86
GM IR maize	416	2,367	1.57	0.77
GM IR cotton	1,732	7,510	12.1	6.68
Others	25	66	n/a	n/a
Totals	**5,027 [5,588]**	**24,244 [26,975]**	**6.0 [6.7]**	**3.6 [4.0]**

Note. HT=herbicide-tolerant, IR=insect resistant, Others = Virus-resistant papaya and squash, rootworm-resistant maize.Bracketed figures include second crop benefits in Argentina. Totals for the value shares exclude 'other crops' (i.e., relate to the 4 main crops of soybeans, maize, canola and cotton). Farm income calculations are net farm income changes after inclusion of impacts on costs of production (e.g., payment of seed premia, impact on crop protection expenditure).

adding the equivalent of 6.05% to the $47 billion value of the global soybean crop in 2005. These economic benefits should, however, be placed within the context of a significant increase in the level of soybean production in the main GM adopting countries. Since 1996, both the soybean *area* and *production* in the leading soybean producing countries of the US, Brazil, and Argentina increased by 58% and 65%, respectively.

Substantial gains have also arisen in the cotton sector through a combination of higher yields and lower costs. In 2005, cotton farm income levels in the GM adopting countries increased by $1.9 billion and since 1996, the sector has benefited from an additional $8.44 billion. The 2005 income gains are equivalent to adding 13.3% to the value of the cotton crop in these countries, or 7.3% to the $26 billion value of total global cotton production. This is a substantial increase in value added terms for two new cotton seed technologies.

Significant increases to farm incomes have also resulted in the maize and canola sectors. The combination of GM IR and GM HT technology in maize has boosted farm incomes by more than $3.1 billion since 1996. In the North American canola sector, an additional $893 million has been generated.

Table 2 summarizes farm income impacts in key GM adopting countries. This highlights the important farm income benefit arising from GM HT soybeans in Argentina, GM IR cotton in China, and a range of GM culti-

Table 2. GM crop farm income benefits 1996-2005 selected countries (million US $).

Country	GM HT soybeans	GM HT maize	GM HT cotton	GM HT canola	GM IR maize	GM IR cotton	Total
US	7,570	771	919	101	1,957	1,627	**12,945**
Argentina	5,197	0.2	4.0	n/a	159	29	**5,389.2**
Brazil	1,367	n/a	n/a	n/a	n/a	n/a	**1,367**
Paraguay	132	n/a	n/a	n/a	n/a	n/a	**132**
Canada	69	24	n/a	792	145	n/a	**1,031**
South Africa	2.2	0.3	0.2	n/a	59	14	**75.7**
China	n/a	n/a	n/a	n/a	n/a	5,168	**5,168**
India	n/a	n/a	n/a	n/a	n/a	463	**463**
Australia	n/a	n/a	4.1	n/a	n/a	150	**154.1**
Mexico	n/a	n/a	n/a	n/a	n/a	55	**55**
Philippines	n/a	n/a	n/a	n/a	8	n/a	**8**
Spain	n/a	n/a	n/a	n/a	28	n/a	**28**

Note. Argentine GM HT soybeans include second crop soybeans benefits. N/a = not applicable.

Table 3. GM crop farm income benefits 2005: Developing versus developed countries (million US $).

Crop	Developed	Developing	% Developed	% Developing
GM HT soybeans	1,183	1,658	41.6	58.4
GM IR maize	364	53	86.5	13.5
GM HT maize	212	0.3	99.9	0.1
GM IR cotton	354	1,378	20.4	79.6
GM HT cotton	163	3	98.4	1.6
GM HT canola	195	0	100	0
GM VR papaya & squash	25	0	100	0
Total	**2,496**	**3,092**	**45**	**55**

Note. Developing countries include all countries in South America.

vars in the US. It also illustrates the growing level of farm income benefits being obtained in developing countries such as South Africa, Paraguay, India, the Philippines, and Mexico.

In terms of the division of the economic benefits obtained by farmers in *developing* countries relative to farmers in *developed* countries, GM crop farm income benefits 2005: Developing versus developed countries (million US $).Table 3 shows that in 2005, the majority of the farm income benefits (55%) have been earned by *developing* country farmers. The vast majority of these income gains for developing country farmers have been from GM IR cotton and GM HT soybeans.[6]

Examination of the cost farmers pay for accessing GM technology relative to the total gains derived shows that across the four main GM crops, the total cost was equal to about 26% of the total farm income gains (Table 4). For farmers in *developing* countries the total cost is equal to roughly 13% of total farm income gains, while for farmers in *developed* countries the cost is about 38% of the total farm income gain. While circumstances vary between countries, the higher share of total gains derived by farmers in *developing* countries relative to farmers in *developed* countries reflects factors such as weaker provision and enforcement of intellectual property rights.

In addition to these quantifiable direct impacts on farm profitability, there have been other important, indirect impacts that are more difficult to quantify (e.g., facilitation of adoption of reduced- or no-tillage systems, reduced production risk, convenience, reduced exposure of farmers and farm workers to pesticides, and improved crop quality). These less tangible benefits have often been cited by GM-adopting farmers as having been important influences for adoption of the technology and, therefore, exclusion of these impacts from the analysis in this paper is a limitation of the methodology, although it suggests that the farm income benefits quantified are conservative.

Table 4. Cost of accessing GM technology (in % terms) relative to the total farm income benefits, 2005.

Crop	All farmers	Developed countries	Developing countries
GM HT soybeans	21	32	10
GM IR maize	44	43	48
GM HT maize	38	38	81
GM IR cotton	21	41	13
GM HT cotton	44	43	65
GM HT canola	47	47	n/a
Total	**26**	**38**	**13**

Note. N/a = not applicable. Cost of accessing the technology is based on the seed premia paid by farmers for using GM technology relative to its conventional equivalent.

Environmental Impacts from Changes in Insecticide and Herbicide Use

Methodology

The most common way in which changes in pesticide use with GM crops have been presented is in terms of the volume (quantity) of pesticide applied. While comparisons of total pesticide volume used in GM and non-GM crop production systems can be a useful indicator of environmental impacts, it is an imperfect measure because it does not account for differences in the specific pest-control programs used in GM and non-GM cropping systems. For example, different specific products used in GM versus conventional crop systems, dif-

6. *The authors acknowledge that the classification of different countries into developing or developed country status affects the distribution of benefits between these two categories of country. The definition used in this paper is consistent with the definition used by James (2006).*

Table 5. Impact of changes in the use of herbicides and insecticides from growing GM crops globally, 1996-2005.

Trait	Change in volume of active ingredient used (million kg)	Change in field EIQ impact (in terms of million field EIQ/ha units)	% change in ai use in GM growing countries	% change in environmental impact in GM growing countries
GM HT soybeans	-51.4	-4,865	-4.1	-20.0
GM HT maize	-36.5	-845	-3.4	-4.0
GM HT cotton	-28.6	-1,166	-15.1	-22.7
GM HT canola	-6.3	-310	-11.1	-22.6
GM HT maize	-7.0	-403	-4.1	-4.6
GM IR cotton	-94.5	-4,670	-19.4	-24.3
Totals	**-224.3**	**-12,259**	**-6.9**	**-15.3**

ferences in the rate of pesticides used for efficacy, and differences in the environmental characteristics (mobility, persistence, etc.) are all masked in general comparisons of total pesticide volumes used.

To provide a more robust measurement of the environmental impact of GM crops, the analysis presented below includes both an assessment of pesticide active ingredient use, as well as an assessment of the specific pesticides used via an indicator known as the Environmental Impact Quotient (EIQ). This universal indicator, developed by Kovach, Petzoldt, Degni, and Tette (1992) and updated annually, effectively integrates the various environmental impacts of individual pesticides into a single 'field value per hectare.' This provides a more balanced assessment of the impact of GM crops on the environment as it draws on all of the key toxicity and environmental exposure data related to individual products (as applicable to impacts on farm workers, consumers, and ecology) and provides a consistent and comprehensive measure of environmental impact. Readers should note, however, that the EIQ is an indicator *only* and therefore does not take into account all environmental issues and impacts.

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 15.3. 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 16.83/ha.

The EIQ indicator used is therefore a comparison of the field EIQ/ha for conventional versus GM crop production systems, with the total environmental impact or load of each system a direct function of respective field EIQ/ha values and the area planted to each type of production (GM versus non-GM). The use of environmental indicators is commonly used by researchers and the EIQ indicator has been cited by Brimner, Gallivan, and Stephenson (2004) in a study comparing the environmental impacts of GM and non-GM canola.

The EIQ methodology was used to calculate and compare typical EIQ values for conventional and GM crops and then aggregate these values to a national level. The level of pesticide use on the respective areas planted to conventional and GM crops in each year was compared with the level of pesticide use that would otherwise have probably occurred if the whole crop, in each year, had been produced using conventional technology. This is based on the approach used by Sankula and Blumenthal (2003)[7] that identifies and utilizes typical herbicide or insecticide treatment regimes for conventional and GM crops provided by extension and research advisors in each sector or country. This approach was selected to address gaps in the availability of herbicide or insecticide usage data in most countries that differentiate between GM and conventional crops. Additionally, this allows comparisons to be made between GM and non-GM cropping systems when GM accounts for a large proportion of the total crop planted area. For example, in the case of soybeans in several countries, more than 60% of the total soybean crop planted area are GM. It is not reasonable to compare the production practices of these two groups as the remaining non-adopters may be farmers in a region characterized by lower-than-average weed or pest pressures or with a tradition of less intensive production systems, and hence, lower-than-average pesticide use.

Results

GM crops have contributed to a significant reduction in the global environmental impact of production agriculture (Table 5). Since 1996, the use of pesticides was reduced by 224 million kg of active ingredient (a 6.9%

7. *Also applied by others, e.g., Kleiter et al. (2005).*

Table 6. Reduction in 'environmental impact' from changes in pesticide use associated with GM crop adoption by country, 1996-2005, in selected countries (% reduction in field EIQ values).

Country	GM HT soybeans	GM HT maize	GM HT cotton	GM HT canola	GM IR maize	GM IR cotton
US	29	4	24	38	5	23
Argentina	21	NDA	NDA	n/a	0	4
Brazil	6	n/a	n/a	n/a	n/a	n/a
Paraguay	13	n/a	n/a	n/a	n/a	n/a
Canada	9	5	n/a	22	NDA	n/a
South Africa	7	0.44	6	n/a	2	NDA
China	n/a	n/a	n/a	n/a	n/a	28
India	n/a	n/a	n/a	n/a	n/a	3
Australia	n/a	n/a	4	n/a	n/a	22
Mexico	n/a	n/a	n/a	n/a	n/a	NDA
Spain	n/a	n/a	n/a	n/a	30	n/a

Note. N/a = not applicable. NDA = No data available. Zero impact for GM IR maize in Argentina is due to the negligible (historic) use of insecticides on the Argentine maize crop.

reduction) and the overall environmental impact associated with pesticide use on these crops was reduced by 15.3%. In absolute terms, the largest environmental gain has been associated with the adoption of GM HT soybeans and reflects the large share of global soybean plantings accounted for by GM soybeans. The volume of herbicide use in GM soybeans decreased by 51 million kg since 1996 (a 4.1% reduction) and the overall environmental impact decreased by 20%. It should be noted that in some countries, such as in South America, the adoption of GM HT soybeans has coincided with increases in the volume of herbicides used relative to historic levels. This largely reflects the facilitating role of the GM HT technology in accelerating and maintaining the switch away from conventional tillage to no- or low-tillage production systems with their inherent environmental benefits. This net increase in the volume of herbicides used should, therefore, be placed in the context of the reduced GHG emissions arising from this production system change and the general dynamics of agricultural production system changes.

Major environmental gains have also been derived from the adoption of GM IR cotton. These gains were the largest of any crop on a per-hectare basis. Since 1996, farmers have used 95.5 million kg less insecticide in GM IR cotton crops (a 19.4% reduction), and reduced the environmental impact by 24.3%. Important environmental gains have also arisen in the maize and canola sectors. In the maize sector, pesticide use decreased by 43 million kg and the environmental impact decreased due to a combination of reduced insecticide use (4.6%) and a switch to more environmentally-benign herbicides (4%). In the canola sector, farmers reduced herbicide use by 6.3 million kg (an 11% reduction) and the environmental impact has fallen by 23% because of a switch to more environmentally-benign herbicides. The impact of changes in insecticide and herbicide use at the country level for the main GM adopting countries is summarized in Table 6.

In terms of the division of the environmental benefits associated with less insecticide and herbicide use for farmers in *developing* countries relative to farmers in *developed* countries, Table 7 shows that in 2005 the majority of the environmental benefits associated with lower insecticide and herbicide use have been for *developing* country farmers. The vast majority of these environmental gains have been from the use of GM IR cotton and GM HT soybeans.

Impact on Greenhouse Gas (GHG) Emissions

Methodology

Reductions in the level of GHG emissions from GM crops derive from two principle sources (Conservation Technology Information Center (CTIC), 2004; Fabrizzi, Morónc, & García, 2003; Jasa, 2002; Lazarus & Selley, 2005; Reicosky, 1995; Robertson et al., 2000; Johnson et al., 2005; Liebig et al., 2005; West & Post, 2002). 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 example, Lazarus and Selley (2005) estimated that one pesticide spray application uses 1.045 liters of fuel,

Table 7. GM crop environmental benefits from lower insecticide and herbicide use, 2005: Developing versus developed countries.

Crop	% of total reduction in environmental impact: Developed countries	% of total reduction in environmental impact: Developing countries
GM HT soybeans	53	47
GM IR maize	92	8
GM HT maize	99	1
GM IR cotton	15	85
GM HT cotton	99	1
GM HT canola	100	0
Total	**46**	**54**

Note. Developing countries include all countries in South America.

which is equivalent to 2.87 kg/ha of carbon dioxide emissions. In this analysis, we used the conservative assumption that only GM IR crops reduced spray applications and ultimately GHG emissions.

In addition to the reduction in the number of herbicide applications, there has been a shift from conventional tillage to reduced- or no-till. This has had a marked effect on tractor fuel consumption due to energy-intensive cultivation methods being replaced with no- or reduced-tillage and herbicide-based weed control systems. The GM HT crop in which this is most evident is GM HT soybeans. Here, adoption of the technology has made an important contribution to facilitating the adoption of reduced- or no-tillage farming.[8] Before the introduction of GM HT soybean cultivars, no-tillage systems were practiced by some farmers using a number of herbicides and with varying degrees of success. The opportunity for growers to control weeds with a non-residual foliar herbicide as a "burndown" pre-seeding treatment, followed by a post-emergent treatment when the soybean crop became established, has made the no-tillage system more reliable, technically viable, and commercially attractive. These technical advantages combined with the cost advantages have contributed to the rapid adoption of GM HT cultivars and the near doubling of the no-tillage soybean area in the US (also more than a five-fold increase in Argentina). In both countries, GM HT soybeans are estimated to account for 95% of the no-tillage soybean crop area.

8. *See, for example, CTIC (2002).*

Substantial growth in no-tillage production systems have also occurred in Canada, where the no-tillage canola area increased from 0.8 million ha to 2.6 million ha, which is equal to about half of the total canola area, between 1996 and 2005 (95% of the no-tillage canola area is planted with GM HT cultivars). Similarly the area planted to no-tillage in the US cotton crop increased from 0.2 million ha to 1 million ha over the same period (of which 86% is planted to GM HT cultivars).

The fuel savings we used resulting from changes in tillage systems are drawn from estimates from studies by Jasa (2002) and CTIC (2004). The adoption of no-tillage farming systems is estimated to reduce cultivation fuel usage by 32.52 liters/ha compared with traditional conventional tillage, and 14.7 liters/ha compared with the average of reduced-tillage cultivation. In turn, this results in reductions of carbon dioxide emissions of 89.44 kg/ha and 40.43 kg/ha, respectively.

Secondly, the use of *no-till* and *reduced-till*[9] farming systems that utilize less plowing increase the amount of organic carbon (in the form of crop residue) that is stored or sequestered in the soil. This carbon sequestration reduces carbon dioxide emissions to the environment. Rates of carbon sequestration have been calculated for cropping systems using normal tillage and reduced tillage and these were incorporated in our analysis on how GM crop adoption has played an important facilitating role in increasing carbon sequestration, and ultimately on reducing the release of carbon dioxide into the atmosphere. Of course, the amount of carbon sequestered varies by soil type, cropping system and eco-region. In North America, the International Panel on Climate Change estimates that the conversion from conventional tillage to no-tillage systems stores between 50 kg carbon/ha per year and 1,300 kg carbon/ha per year (average 300 kg carbon/ha per year). In the analysis presented below, a conservative saving of 300 kg carbon/ha per year was applied to all no-tillage agriculture and 100 kg carbon/ha per year was applied to reduced-tillage agriculture. Where some countries aggregate their no- and reduced-till data, the reduced-tillage savings value of 100 kg carbon/ha per year was used. One kg of carbon sequestered is equivalent to 3.67 kg of car-

9. *No-till farming means that the ground is not plowed 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.*

Table 8. Impact of GM crops on carbon sequestration impact in 2005 (car equivalents).

Crop/trait/country	Permanent carbon dioxide savings arising from reduced fuel use (million kg of carbon dioxide)	Average family car equivalents removed from the road for a year from the permanent fuel savings	Potential additional soil carbon sequestration savings (million kg of carbon dioxide)	Average family car equivalents removed from the road for a year from the potential additional soil carbon sequestration
US: GM HT soybeans	176	78,222	2,195	975,556
Argentina: GM HT soybeans	546	242,667	4,340	1,928,889
Other countries: GM HT soybeans	55	24,444	435	193,333
Canada: GM HT canola	117	52,000	1,083	481,520
Global GM IR cotton	68	30,222	0	0
Total	**962**	**427,556**	**8,053**	**3,579,298**

Note. Data assumes that an average family car produces 150 grams of carbon dioxide of km. A car does an average of 15,000 km/year and therefore produces 2,250 kg of carbon dioxide/year.

bon dioxide. These assumptions were applied to the reduced pesticide spray applications data on GM IR crops, derived from the farm income literature review, and the GM HT crop areas using no or reduced tillage (limited to the GM HT soybean crops in North and South America and GM HT canola crop in Canada).[10]

Table 8 summarizes the impact on GHG emissions associated with the planting of GM crops between 1996 and 2005. In 2005, the permanent carbon dioxide savings from reduced fuel use associated with GM crops was 0.962 billion kg. This is equivalent to removing 430,000 cars from the road for a year.

The additional soil carbon sequestration gains resulting from reduced tillage with GM crops accounted for a reduction in 8.05 billion kg of carbon dioxide emissions in 2005. This is equivalent to removing nearly 3.6 million cars from the roads for a year. In total, the carbon savings from reduced fuel use and soil carbon sequestration in 2005 were equal to removing 4 million cars from the road (equal to 17% of all registered cars in the UK).

10. *Due to the likely small scale impact and/or lack of tillage-specific data relating to GM HT maize and cotton crops (and the US GM HT canola crop), analysis of possible GHG emission reductions in these crops have not been included in the analysis. The no- or reduced-tillage areas to which these soil carbon reductions were applied were limited to the increase in the area planted to no- or reduced-tillage in each country since GM HT technology has been commercially available. In this way, the authors have tried to avoid attributing no- or reduced-tillage soil carbon sequestration gains to GM HT technology on cropping areas that were using no- or reduced-tillage cultivation techniques before GM HT technology became available.*

Concluding comments

This study quantified the cumulative global impact of GM technology between 1996 and 2005 on farm income, pesticide usage, and greenhouse gas emissions. The analysis shows that there have been substantial economic benefits at the farm level, amounting to a cumulative total of $27 billion. The majority of this has been derived by farmers in developing countries. GM technology has also resulted in 224 million kg less pesticide use by growers and a 15.3% reduction in the environmental impact associated with pesticide use. GM crops have also made a significant contribution to facilitating a reduction in greenhouse gas emissions of 9 billion kg in 2005, equivalent to removing 4 million cars from the roads for a year.

The impacts identified are, however, probably conservative, reflecting the limitations of the methodologies used to estimate each of the three main categories of impact and the limited availability of relevant data. As such, subsequent research might usefully extend the analysis to incorporate more sophisticated consideration of dynamic economic impacts and some of the less tangible economic impacts (e.g., on labor savings). Further analysis of the environmental impact might also usefully include additional environmental indicators, such as impact on soil erosion.

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Appendix

See below tables for key baseline assumptions and sources for the farm income impact analysis.

Table A1. GM HT crops.

Crop	Country	Yield effect	Cost of technology ($/ha)	Cost savings excluding cost of technology & sources ($/ha)
Soybeans	**US**	None	1996-2002=$14.82; 2003=$17.30; 2004 onwards=$19.77	1996-97 =$25.20 (Marra et al., 2002); 1998-2000=$33.90 (Gianessi & Carpenter, 1999); 2002=$73.40 (Carpenter & Gianessi, 2001); 2003=$78.50; 2004 onwards=$63.30 (Sankula & Blumenthal, 2003, 2005)
	Argentina	None	All years to 2001=$3-$4; then decreasing to reflect increasing share of farm saved seed (to $1.24/ha in 2005)	$24-$30; varies each year according to exchange rate; based on Qaim and Traxler (2002)
	Brazil	None	Same as Argentina, except 2003=$9; 2004=$15; 2005=$16	2004=$88; applied to all other years at prevailing exchange rate; based on data from the Parana Department of Agriculture (2005)
	Paraguay & Uruguay	None	Same as Argentina	Same as Argentina; no country-specific analysis identified
	Canada	None	1997-2002=$32 Canadian; 2003=$48 Canadian; 2004 & 2005=$45 Canadian[a]	1997-2005=Range of $47 to $89 Canadian[a]; based on George Morris Centre (2004)
	South Africa	None	Each year =170 Rand[a]	Each year=230 Rand[a]; based on Monsanto South Africa (personal communication, 2005)
	Romania	+31% & 2% price premia from cleaner crops all years	1999 & 2000=$160; 2001=$148; 2002=$135; 2003 & 2004=$130; 2005=$121; all inclusive of 4 liters of Roundup	1999-2005=$140-$239; based on Brookes (2004)
Maize	**US**	None	All years=$14.80	All years to 2003=$39.90; 2004-2005=$40.55; based on Carpenter and Gianessi (2001) and Sankula and Blumenthal (2003, 2005)
	Canada	None	All years=$27 Canadian[a]	All years=$48.75 Candian[a]; based on Monsanto Canada (personal communication, 2005)
	South Africa	None	All years=80 Rand[a]	All years=107.50 Rand[a]; based on Monsanto South Africa (personal communication, 2005)
	Argentina	None	$14	$16-$17
Cotton	**US**	None	1996-2000=$12.85; 2001-2003=$21.32; 2004-2005=$34.55	1996-2000=$34.12; 2001-2003=$66.59; 2004-2005=$83.35; (Carpenter & Gianessi, 2001 ; Sankula & Blumenthal, 2003, 2005)
	Australia	None	All years from 2000=$50 Australian[a]	All years from 2000=$60 Australian; based on Doyle et al. (2003) and Monsanto Australia (personal communication, 2005)
	South Africa	None	All years from 2001-2004=133 Rand; 2005=101 Rand[a]	All years from 2001=160 Rand[a]; based on Monsanto South Africa (personal communication, 2005)
Canola	**US**	All years = +6%	**Glyphosate tolerant:** 1999-2001=$29.50; 2002 onwards=$33; **Glufosinate tolerant:** all years=$17.30	**Glyphosate tolerant:** 1999-2001=$60.75; 2002-2003=$67; 2004 onwards=$69; **Glufosinate tolerant:** all years to 2003=$44.89; 2004 onwards=$44; based on Carpenter and Gianessi (2001) and Sankula and Blumenthal (2003, 2005)
	Canada	All years = +10.7	All years=$44.63 Canadian[a]	All years=$39 Canadian[a]; based on Canola Council of Canada (2001)

[a]*Converted to US $ at prevailing exchange rate.*

Table A2. GM IR crops.

Crop	Country	Yield effects	Cost of technology ($/ha)	Cost savings excluding cost of technology & sources ($/ha)
Maize	**US**	All years = +5%, reflecting lower of range of impacts identified by Carpenter and Gianessi (2001), Sankula and Blumenthal (2003), Marra et al. (2002); range of average impacts being +5% to +6.7%	1996-1997=$25; 1998-1999=$20; 2000 onwards=$22	All years=$15.50; based on James (2003), Carpenter and Gianessi (2001), Sankula and Blumenthal (2003), Marra et al. (2002)
	Canada	All years= +5%	Same as US	Same as US; no specific Canadian studies available, but impacts qualitatively confirmed by Monsanto Canada (personal communication, 2005)
	Argentina	All years= +9%	Same as US	All years=0; no specific Argentine studies identified, but values confirmed by Trigo (2005). Yield impact based on James (2003)
	Philippines	All years= +24.5% plus 10% quality premia	$36	$3. All impact data based on Yorobe (2004), Ramon (2005)
	Spain	All years= +6.3%, reflecting a conservatively estimated average impact when compared with positive impacts of +10% to +15% in the main (high pest infestation) user regions	1998-1999=30 euros; 2000=28 euros; 2001 onwards=18.5 euros[a]	All years=42 euros[a]; based on Brookes (2003)
Cotton	**US**	Bollgard I: 1996-2002= 9% (based on the lower of identified average yield impacts from Carpenter & Gianessi, 2001; Sankula & Blumenthal, 2003; Marra et al., 2002); Bollgard II: 2003 onwards= 11% (Mullins & Hudson, 2004)	1996-2002=$58.27; 2003 onwards=$68.32	$63.26 1996-2002, 2003 onwards=$74.10; based on Carpenter and Gianessi (2001), Sankula and Blumenthal (2003, 2005), Marra et al. (2002), Mullins and Hudson (2004)
	China	1997-1999= +8%; 2000 onwards= 10%	All years=$46.30	2000=$261; 2001=$438; average of these used all other years; based on Pray, Huang, Hu, and Rozelle (2002)
	Australia	None	1996-1997=$245 Australian; 1998=$155 Aus; 1999-2001=$138 Aus; 2002=$155 Aus; 2003=$167 Aus; 2004=$190 Aus; 2005=$250 Aus	1996=$151 Aus; 1997=$157 Aus; 1998=$188 Aus; 1999=$172 Aus; 2000-2002=$267 Aus; 2003=$598 Aus; 2004=$509 Aus; 2005=$553 Aus[a]; based on Fitt (2003), Doyle (2005), James (2002)
	Argentina	All years= +30%	All years=$86, except 2005=$40 (Monsanto Comercial Mexico, 2004)	All years=$17.47; based on Qaim and De Janvry (2002, 2005)
	South Africa	All years= 24%	All years=376 Rand[a]	All years=127 Rand[a]; based on Ismael, Bennett, Morse, and Buthelezi (2002), James (2002), Kirsten et al. (2002)

Cotton, cont'd	**Mexico**	1996-2004= 3%-37%; year specific data used. 2205 based on 2004	1996 and 1999 onwards=540 pesos[a]; 1997=$65; 1998=$56	1996 and 1999 onwards=985 pesos[a]; 1997=$121; 1998=$94; based on Traxler, Godoy-Avilla, Falck-Zepeda, and Espinoza-Arellano (2001), Monsanto Comercial Mexico (2004)
	India	2002= 45%; 2003= 63%; 2004= 54%; 2005= 64%	2002=2,636 Rupees; 2003=2,512 Rupees; 2004=2,521 Rupees[a]	2002=2,636 Rupees; 2003-2004=2,521 Rupees; 2005=1,250 Rupees[a]; based on Bennett, Ismael, Kambhampati, and Morse (2004), Asia-Pacific Consortium on Agricultural Biotechnology (2006)

[a]*Converted to US $ at prevailing exchange rate.*

Table A3. Others.

Country/crop	Yield effects	Cost of technology ($/ha)	Cost savings excluding cost of technology & sources ($/ha)
US & Canada: GM IR corn rootworm maize	3%	$42	2003=$32; 2004 onwards=$37; based on Sankula and Blumenthal (2003, 2005), Rice (2004)
US: GM virus resistant papaya	1999-2005= between 16% and 50%	1999 to 2003=$0; 2004 onwards=$42	None; based on Sankula and Blumenthal (2003, 2005)

[a]*Converted to US $ at prevailing exchange rate.*