GM Crops: The Global Economic and Environmental Impact—The First Nine Years 1996–2004

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2005 represents the tenth planting season since genetically modified (GM) crops were first grown in 1996. This milestone provides the opportunity to critically assess the impact this technology is having on global agriculture. This study 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 a cumulative total of $27 billion. The technology has reduced pesticide spraying by 172 million kg and has reduced the environmental footprint associated with pesticide use by 14%. The technology has also significantly reduced the release of greenhouse gas emissions from agriculture, which is equivalent to removing five million cars from the roads.

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

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. Several studies have investigated the economic and environmental perspectives of GM crops, but these have usually been limited by trait, country, and/or year. This study therefore aims to quantify these impacts cumulatively for the period 1996–2004 through a combination of collating and extrapolating economic analysis findings from past studies and undertaking new environmental impact analysis. This global cumulative analysis over a nine-year period will better identify consistent trends in the technology impact over time as well as identify salient differences in impact between crops, traits, and countries.

The economic impact analysis concentrates on farm income effects, because this is a primary driver of adoption amongst farmers 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 impact on the environmental load from crop production. Previous investigations have been limited to an examination of changes in pesticide volumes with GM crops, whereas this study expands the analysis and includes a more robust assessment of the specific pesticide products used in different production systems and their environmental load impact. Lastly, we investigate for the first time the contribution of GM crops towards reducing global greenhouse gas (GHG) emissions because of the importance of this issue to the global environment.

Methodology

The report has been compiled based largely on extensive analysis of existing farm-level impact data from GM crops. Primary data for impacts of commercial cultivation were, of course, not available for every crop, in every year, and for each country, but all identified representative previous research has been utilized. The findings of this research have been used as the basis for the analysis presented,[1] 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 footprint of the technology at the farm level does vary widely, both between and within regions and countries. As a result, the impact of this technology, and any new technology, GM or otherwise, is subject to variation at the local level. Therefore, 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,

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1. *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 average*

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.

Farm Income Effects

Methodology

The primary 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 nine-year period examined (Table 1). 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 yield and price changes and accounts for the possible impact of GM

Table 1. Key baseline assumptions and sources for the farm income impact analysis.

Crop	Country	Yield effect	Cost of technology ($/ha)	Cost savings excluding cost of technology & sources ($/ha)
GM HT soybeans	US	None	$14.82 1996–2002 & $17.3 2003 onwards	$25.2 1996–97 (Marra et al., 2002), $33.9 1998–2000 (Gianessi & Carpenter, 1999), $73.4 2003 (Carpenter & Gianessi, 2001), $78.5 2004 (Sankula & Blumenthal, 2004)
	Argentina	None	$3–4 all years	$24–30; varies each year according to exchange rate (Qaim & Traxler, 2002)
	Brazil	None	As Argentina, except 2004, when $15	$88 in 2004, applied to all other years at prevailing exchange rate
	Paraguay & Uruguay	None	As Argentina	As Argentina; no country-specific analysis identified
	Canada	None	C$32 1997–02, C$48 2003, and C$45 2004[a]	C$47–89 1997–2004[a] (George Morris Center, 2004)
	South Africa	None	R170 each year[a]	R230 each year[a] (Monsanto S. Africa, personal communication, 2005)
	Romania	+31% & 2% price premia from cleaner crops all years	$160 1999 & 2000, $148 2001, $135 2002, $130 2003 all inclusive of 4 litres of Roundup	$140–239 1999–2003 (Brookes, 2003)
GM HT maize	US	None	$14.8 all years	$39.9 all years (Carpenter & Gianessi, 2001; Sankula & Blumenthal, 2004)
	Canada	None	C$27 all years[a]	C$48.75 all years[a] (Monsanto Canada, personal communication, 2005)
	South Africa	None	R80 all years[a]	R107.5 all years[a] (Monsanto S. Africa, personal communication, 2005)
GM HT cotton	US	None	$12.85 1996–2000, $21.32 2001 onwards	$34.12 1996–2000, $66.59 2001 onwards[a] (Carpenter & Gianessi, 2001; Sankula & Blumenthal, 2004)
	Australia	None	AU$50 all years from 2000[a]	AU$60 all years from 2000 (Doyle et al., 2002; Monsanto Australia, personal communication, 2005)
	South Africa	None	R133 all years from 2001[a]	R160 all years from 2001[a] (Monsanto S. Africa, personal communication, 2005)
GM HT canola	US	+6% all years	$29.5 1999–2001, $33 2002 onwards for glyphosate tolerant & $17.3 all years for glufosinate tolerant	$60.75 1999–2001, $67 2002 onwards glyphosate tolerant, $44.89 all years glufosinate tolerant (Carpenter & Gianessi, 2001; Sankula & Blumenthal, 2004)
	Canada	+10.7 all years	C$44.03 all years[a]	C$39 all years[a] (Canola Council, 2001)

Table 1. (continued) Key baseline assumptions and sources for the farm income impact analysis.

Crop	Country	Yield effect	Cost of technology ($/ha)	Cost savings excluding cost of technology & sources ($/ha)
GM IR maize	US	=5% all years	$25 1996 & 1997, $20 1998 & 1999, $22 2000 onwards	$15.5 all years (James, 2002; Carpenter & Gianessi, 2001; Sankula & Blumenthal, 2004; Marra et al., 2002)
	Canada	+5% all years	As US	As US; no specific Canadian studies available but impacts qualitatively confirmed by Monsanto Canada (personal communication, 2005)
	Argentina	+9% all years	As US	Nil all years; no specific Argentine studies identified but values confirmed by Trigo (2005); yield impact based on James (2003)
	Philippines	+25% all years	PS2,800 2003 & 2004[a]	PS800 2003 & 2004[a] (James, various)
	Spain	+6.3% all years	30 euros 1998 & 1999, 28 euros 2000, 18.5 euros 2001 onwards[a]	42 euros all years[a] (Brookes, 2002)
GM IR cotton	US	9% 1996-2002, 11% 2003 & 2004	$58.27 1996–2002, $72.84 2003 & 2004	$63.26 1996–2002, $74.1 2003 & 2004 (Carpenter & Gianessi, 2001; Sankula & Blumenthal, 2004; Marra et al., 2002; Mullins & Hudson, 2004)
	China	+8% 1997-1999, 10% 2000 onwards	$42 all years	$261 2000, $438 2001; average of these used all other years (Pray et al., 2002)
	Australia	None	AU$245 1996 & 1997, AU$155 1998, AU$138 1999–2002, AU$250 2003 & 2004	AU$151 1996, AU$157 1997, AU$188 1998, AU$172 1999, AU$267 2000–2002, AU$347 2003 & 2004[a] (Fitt, 2003; Doyle, 2005; James, 2002)
	Argentina	+30% all years	$86 all years	$17.47 all years (Qaim & De Janvry, 2002, 2005)
	South Africa	24% all years	R376 all years[a]	R127 Rand all years[a] (Ismael et al., 2002; James, 2002; Gouse & Kirsten, 2002)
	Mexico	3%-37% 1996-2004: year specific data used	PS540 1996 and 1999 onwards[a], $65 1997, $56 1998	PS985 pesos 1996 and 1999 onwards[a], $121 1997 and $94 1998 (Traxler et al., 2001; Monsanto Mexico, 2005)
	India	45% 2002, 63% 2003, 54% 2004	Rs2,636 2002, Rs2,512 2003, Rs2,521 2004[a]	Rs2,032 2002, Rs1,767 2003 & Rs1,900 2004[a] (Bennett et al., 2004)
Others	US: GM IR corn rootworm maize	3% 2003 & 2004	$42 both years	$32 both years (Sankula & Blumenthal, 2004)
	US: GM virus resistant papaya	Between 16% and 50% 1999-2004	None 1999–2003, $119 2004	None (Sankula & Blumenthal, 2004)

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

crop adoption on global crop supply and world prices. Clearly, this simplistic approach may overstate or understate the real impact of GM technology; the authors acknowledge that this represents a weakness of the research. However, the use of current prices does incorporate some degree of dynamic into the analysis that would otherwise be missing if constant prices had been used. Where yield impacts have been identified in stud-

ies for one or a limited number of years, these 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.[2]

Table 2. Farm-level income impact of using GM HT soybeans in Argentina, 1996–2004.

Year	Cost savings ($/ha)	Net saving on costs (inclusive of cost of technology ($/ha)	GM HT area (million ha)	Increase in farm income at a national level ($ millions)	Value of production ($ million)	Increase in farm income from facilitating additional second cropping ($ millions)
1996	26.10	22.49	0.037	0.90	2,583	0
1997	25.32	21.71	1.756	41.66	2,573	173.8
1998	24.71	21.10	4.80	114.98	3,966	475.2
1999	24.41	20.80	6.64	151.66	3,333	657.4
2000	24.31	20.70	9.00	205.25	4,460	891.0
2001	24.31	20.70	10.93	250.25	5,074	1,081.6
2002	29.00	26.00	12.45	348.90	5,271	1,446.6
2003	29.00	26.00	13.23	386.21	8,618	1,623.6
2004	30.00	27.00	14.06	415.46	7,326	1,701.1

Note. All values for prices and costs denominated in Argentine pesos have been converted to US dollars at the annual average exchange rate in each year.

Example: Farm Income Impact of GM Herbicide-Tolerant Soybeans in Argentina

The analysis of the impact of GM herbicide-tolerant (HT) soybeans in Argentina, summarized in Table 2 and Table 3, is based on data from Qaim and Traxler (2002). The assumed cost of the technology to farmers was $3–4/ha for each year based on the typical seed premiums charged for new seed in 2000 and 2001. This does, however, probably overstate the cost of technology (and understate the farm level cost savings) in subsequent years because of the high proportion (80%) of the Argentine GM soybean crop derived from farm-saved seed on which no seed premium is payable. No positive or negative yield impacts were identified; therefore, all farm income effects are associated with changes in the cost of production. A 0.5% price premium, identified in Qaim and Traxler (2002), has been applied to reflect the impact of the technology on delivering cleaner crops that attract a higher price.

2. *The average base yield has been adjusted downwards (if necessary) to take account of 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 3. Argentina second-crop soybeans.

Year	Second-crop area (million ha)	Increase in income linked to GM HT system (million $)	Additional production (million tonnes)
1996	0.45	Negligible	Negligible
1997	0.65	173.8	0.258
1998	0.8	475.2	0.807
1999	1.4	657.4	2.2
2000	1.6	891.0	2.6
2001	2.4	1,081.6	4.9
2002	2.7	1,446.5	5.8
2003	2.8	1,623.5	6.4
2004	3.0	1,701.1	5.7

Note. Additional gross margin based on $99/ha 1997–2001, 116/ha in 2002, and $123 in 2003, and $121/ha in 2004 (source: Grupo CEO).

An additional economic impact analyzed was the effect of GM soybeans on the scope for growers planting a second crop of soybeans in the same growing season (usually following on from a wheat crop). The second crop is facilitated substantially by the ease of management of the GM soy crop, which allows farmers to use reduced- or no-tillage systems and hence allows additional time for planting, growing, and harvesting a second crop. The second-cropping benefits presented in Table 3 are based on the gross margin derived from second-crop soybeans multiplied by the total area of second-crop soybeans (less an assumed area of second-crop soybeans that equals the second crop area in 1996).

Table 4. Global farm income benefits from growing GM crops, 1996–2004 (US$ million).

Trait	2004 increase in farm income	1996–2004 increase in farm income	2004 farm income benefit as % of total value of production of these crops in GM adopting countries	2004 farm income benefit as % of total value of global production of these crops
GM HT soybeans	2,440 (4,141)	9,300 (17,351)	5.6 (9.5)	4.0 (6.7)
GM HT maize	152	579	0.6	Less than 0.5
GM HT cotton	145	750	1.4	0.53
GM HT canola	135	713	8.3	1.34
GM IR maize	415	1,932	1.4	0.8
GM IR cotton	1,472	5,726	10.5	5.3
Others	20	37	N/a	N/a
Totals	4,779 (6,480)	19,037 (27,088)	5.3 (7.2)	3.1 (4.2)

Note. HT = herbicide tolerant, IR =insect resistant, Others = Virus-resistant papaya and squash, rootworm-resistant maize. Figures in parentheses include second-crop benefits in Argentina. Totals for the value shares exclude "other crops" (i.e., relate to the four main crops of soybeans, maize, canola, and cotton).

Results

GM technology has had a very positive impact on farm income derived from a combination of enhanced productivity and efficiency gains (Table 4). In 2004, the direct global farm income benefit from GM crops was $4.8 billion. If the additional income arising from second crop soybeans in Argentina is considered, this income gain rises to $6.5 billion. This is equivalent to adding between 3.1% and 4.2% to the value of global production of the four main crops of soybeans, maize, canola, and cotton—a substantial impact. Since 1996, farm incomes have increased by over $19 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 $4.14 billion additional income generated by GM HT soybeans in 2004 has been equivalent to adding 9.5% to the value of the crop in the GM-growing countries, or adding the equivalent of 6.7% to the $62 billion value of the global soybean crop. 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, the soybean area and production in the leading soybean-producing countries of the United States, Brazil, and Argentina increased by 56% and 66%, respectively.

Substantial gains have also arisen in the cotton sector through a combination of higher yields and lower costs. In 2004, cotton farm income levels in the GM-adopting countries increased by $1.62 billion, and since 1996, the sector has benefited from an additional $6.5 billion. The 2004 income gains are equivalent to adding

nearly 12% to the value of the cotton crop in these countries, or 5.8% to the $28 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 insect resistance (IR) and GM HT technology in maize has boosted farm incomes by over $2.5 billion since 1996. In the North American canola sector an additional $713 million has been generated.

Table 5 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 cultivars in the United States. It also illustrates the growing level of farm income benefits being obtained in developing countries such as South Africa, Paraguay, India, and Mexico.

As well as 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, 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; 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 5. GM crop farm income benefits, selected countries, 1996–2004 (US$ million).

	GM HT soybeans	GM HT maize	GM HT cotton	GM HT canola	GM IR maize	GM IR cotton	Total
United States	6,371	564	746	96	1,626	1,301	10,704
Argentina	9,965	n/a	n/a	n/a	120	16	10,101
Brazil	829	n/a	n/a	n/a	n/a	n/a	829
Paraguay	80	n/a	n/a	n/a	n/a	n/a	80
Canada	55	16	n/a	617	119	n/a	807
South Africa	0.8	0.2	0.01	n/a	44	11	56.01
China	n/a	n/a	n/a	n/a	n/a	4,160	4,160
India	n/a	n/a	n/a	n/a	n/a	124	124
Australia	n/a	n/a		n/a	n/a	70	70
Mexico	n/a	n/a	n/a	n/a	n/a	41	41

Note. Argentine GM HT soybeans includes $8,050 billion benefits from second-crop soybeans. N/a = not applicable.

Environmental Impacts from Changes in Insecticide and Herbicide Use

Methodology

The most common way in which changes in pesticide use with GM crops has been presented is in terms of the volume (quantity) of pesticide applied. Although 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 programmes used in GM and non-GM cropping systems. For example, different specific products used in GM versus conventional crop systems, differences in the rate of pesticides used for efficacy, and differences in the environmental characteristics (mobility, persistence, etc.) are 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. Read-

ers should, however, note 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/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 footprint 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 (2004)[3] that identifies and utilizes typical herbicide or insecticide treatment regimes for conventional and GM crops provided by extension and research advi-

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

Table 6. Impact of changes in the use of herbicides and insecticides from growing GM crops globally, 1996–2004.

Trait	Change to pesticide use (million kg)	Change in field EIQ (million field EIQ/ha units)	% change in pesticide ai use	% change in EIQ footprint
GM HT soybeans	-41.4	-4,111	-3.8	-19.4
GM HT maize	-18.0	-503	-2.5	-3.4
GM HT cotton	-24.7	-1,002	-14.5	-21.7
GM HT canola	-4.8	-252	-9.7	-20.7
GM IR maize	-6.3	-377	-3.7	-4.4
GM IR cotton	-77.3	-3,463	-14.7	-17.4
Totals	-172.5	-9,708	-6.3	-13.8

sors 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 differentiates 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, over 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 nonadopters 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 6). Since 1996, the use of pesticides was reduced by 172 million kg (a 6% reduction), and the overall environmental footprint from GM crops was reduced by 14%. 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 41 million kg since 1996 (a 4% reduction), and the overall environmental footprint decreased by 19%. 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 (see below) and the general dynamics of agricultural production system changes.

Major environmental gains have also been derived from the adoption of GM insect resistant (IR) cotton. These gains were the largest of any crop on a per hectare basis. Since 1996, farmers have used 77 million kg less insecticide in GM IR cotton corps (a 15% reduction), and reduced the environmental footprint by 17%. Important environmental gains have also arisen in the maize and canola sectors. In the maize sector, pesticide use decreased by 24 million kg and the environmental footprint decreased by 7.8%, due to a combination of reduced insecticide use and a switch to more environmentally benign herbicides. In the canola sector, farmers reduced herbicide use by 5 million kg (a 10% reduction), and the environmental footprint has fallen by nearly 21% 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 7.

Impact on Greenhouse Gas Emissions

Methodology

Reductions in the level of GHG emissions from GM crops derive from two principal sources (Conservation Technology Information Center, 2002; Fabrizzi, Morónc, & García, 2003; Jasa, 2002; Lazarus & Selley, 2005; Reicosky, 1995; Robertson, Paul, & Harwood, 2000; 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. Lazarus and Selley (2005) reported a reduction of 2.7 kg/ha of carbon dioxide emissions per spray application. In this analysis we used the conservative assumption that only GM IR crops reduced spray applications and ultimately GHG emis-

Table 7. Reduction in environmental footprint from changes in pesticide use associated with GM crop adoption, selected countries, 1996–2004 (% reduction in field EIQ values).

	GM HT soybeans	GM HT maize	GM HT cotton	GM HT canola	GM IR maize	GM IR cotton
United States	28	3	23	32	4.4	20
Argentina	20	n/a	n/a	n/a	0	6.4
Brazil	4	n/a	n/a	n/a	n/a	n/a
Paraguay	10	n/a	n/a	n/a	n/a	n/a
Canada	8	4	n/a	20	NDA	n/a
South Africa	4	0.4	5	n/a	18	NDA
China	n/a	n/a	n/a	n/a	n/a	28
India	n/a	n/a	n/a	n/a	n/a	2.1
Australia	n/a	n/a	3	n/a	n/a	21.2
Mexico	n/a	n/a	n/a	n/a	n/a	NDA

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.

sions. The fuel savings we used resulting from changes in tillage systems are drawn from Carbon Neutral (http://www.carbonneutral.com.au). This source states that the adoption of no-tillage (NT) farming systems reduces cultivation fuel usage by 36.6 litres/ha compared with traditional conventional tillage and 16.7 litres/ha compared with (the average of) chisel plough/disk tillage. In turn, this results in reductions of carbon dioxide emissions of 98.8 kg/ha and 45.0 kg/ha, respectively.

Secondly, the use of no-till and reduced-till[4] 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; these were incorporated in our analysis of how GM crops impact on carbon sequestration and ultimately 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 no-till systems save 300 kg carbon/ha[-1] yr, reduced-tillage systems save 100 kg carbon/ha[-1] yr, and conventional tillage systems deliver a loss of 100 kg carbon/ha[-1] yr. In the analysis presented below, a conservative sav-

ing of 100 kg carbon/ha[-1] yr was applied to all no- and reduced-tillage agriculture to account for the fact that some countries aggregate their no- and reduced-till data. One kg of carbon sequestered is equivalent to 3.67 kg of carbon 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/reduced tillage (limited to the GM HT soybean crops in North and South America and GM HT canola crop in Canada[5]).

Table 8 summarizes the impact on GHG emissions associated with the planting of GM crops between 1996 and 2004. In 2004, the permanent carbon dioxide savings from reduced fuel use associated with GM crops was 1 billion kg. This is equivalent to removing 480,000 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 9.4 billion kg of carbon dioxide emissions in 2004. This is equivalent to removing nearly 4.7 million cars from the roads for a year (equal to 19% of all registered cars in the UK).

Concluding Comments

This study quantified the cumulative global impact of GM technology between 1996 and 2004 on farm income, pesticide usage, and greenhouse gas emissions.

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4. *No-till farming means that the ground is not plowed at all, and 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.*

5. *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 this analysis*

Table 8. Impact of GM crops on carbon sequestration impact in 2004 (car equivalents).

Crop/trait/country	Carbon dioxide savings arising from reduced fuel use (million kg of carbon dioxide)	Carbon dioxide savings from reduced fuel use in family car equivalents removed from the road for a year	Carbon dioxide savings from soil carbon sequestration (million kg of carbon dioxide)	Carbon dioxide savings from soil carbon sequestration in family car equivalents removed from the road for a year
US: GM HT soybeans	322	142,889	3,762	1,672,178
Argentina: GM HT soybeans	532	236,444	4,186	1,860,400
Other countries: GM HT soybeans	73	32,444	569	252,889
Canada: GM HT canola	94	41,778	906	402,800
Global GM IR cotton	61	27,111	0	0
Total	1,082	480,666	9,423	4,188,267

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

The analysis shows that there have been substantial economic benefits at the farm level, amounting to a cumulative total of $27 billion. GM technology has also resulted in 172 million kg less pesticide use by growers and a 14% reduction in the environmental footprint associated with pesticide use. GM crops have also made a significant contribution to reducing greenhouse gas emissions by over 10 billion kg, equivalent to removing five 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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