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Global Impact of Biotech Crops: Environmental Effects, 1996-2008

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This article updates the assessment of the impact commercialized agricultural biotechnology is having on global agriculture from an environmental perspective. It focuses on the impact of changes in pesticide use and greenhouse gas emissions arising from the use of biotech crops. The technology has reduced pesticide spraying by 352 million kg (-8.4%) and, as a result, decreased the environmental impact associated with herbicide and insecticide use on these crops (as measured by the indicator the environmental impact quotient) by 16.3%. The technology has also significantly reduced the release of greenhouse gas emissions from this cropping area, which, in 2008, was equivalent to removing 6.9 million cars from the roads.

Key words: pesticide, active ingredient, environmental impact quotient, carbon sequestration, biotech crops, no tillage.

Introduction

This study presents the findings of research into the global environmental impact of biotech crops since their commercial introduction in 1996. It updates the findings of earlier analyses presented by the authors in *AgBioForum 8*(2&3), *9*(3), and *11*(1).[1]

The environmental impact analysis undertaken focuses on the impacts associated with changes in the amount of insecticides and herbicides applied to the biotech crops relative to conventionally grown alternatives. The analysis also examines the contribution of biotech crops towards reducing global greenhouse gas (GHG) emissions.

The analysis is mostly based on that of existing farm-level impact data from biotech crops. Primary data for impacts of commercial biotech cultivation on both pesticide usage and greenhouse gas emissions is, however, limited and is not available for every crop, in every year and for each country. Nevertheless, all identified, representative, previous research has been utilized. This has been used as the basis for the analysis presented, although, where relevant, primary analysis has been undertaken from base data.

Environmental Impacts from Insecticide and Herbicide Use Changes

Methodology

Assessment of the impact of biotech crops on insecticide and herbicide use requires comparisons of the respective weed- and pest-control measures used on biotech versus the 'conventional alternative' form of production. This presents a number of challenges relating to availability and representativeness. Comparison data ideally derives from farm-level surveys, which collect usage data on the different forms of production. A search of literature on biotech crop impact on insecticide or herbicide use at the trait, local, regional, or national level shows that the number of studies exploring these issues is limited (e.g., Pray, Huang, Hu, & Rozelle, 2002; Qaim & De Janvry, 2005; Qaim & Traxler, 2002) with even fewer (e.g., Brookes, 2003, 2005), providing data to the pesticide (active ingredient) level. Second, national-level pesticide usage survey data is also extremely limited; in fact, there are no published annual pesticide usage surveys conducted by national authorities in any of the countries currently growing biotech traits, and the only country in which pesticide usage data is collected (by private market-research companies) on an annual basis and which allows a comparison between biotech and conventional crops to be made is the United States.[2]

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1. *Readers should note that some data presented in this article are not directly comparable with data presented in previous articles because the current article takes into account the availability of new data and analysis (including revisions to data for earlier years).*

2. *The US Department of Agriculture also conducts pesticide-usage surveys, but these are not conducted on an annual basis (e.g., the last time corn was included was 2005) and do not disaggregate usage by production type (biotech versus conventional).*

Unfortunately, even where national survey data is available on usage, the data on conventional crop usage may fail to be reasonably representative of what herbicides and insecticides might be expected to be used in the absence of biotechnology. When biotech traits dominate total production (e.g., for soybeans, corn, cotton, and canola in the United States since the early 2000s), the conventional cropping dataset used to identify pesticide use relates to a relatively small share of total crop area and therefore is likely to underestimate what usage would probably be in the absence of biotechnology. The reasons why this conventional cropping dataset is unrepresentative of the levels of pesticide use that might reasonably be expected to be used in the absence of biotechnology include the following.

- While the levels of pest and weed problems/damage vary by year, region, and within region, farmers who continue to farm conventionally are often those with relatively low levels of pest or weed problems, and hence see little, if any, economic benefit from using the biotech traits targeted at these agronomic problems. Their pesticide usage levels therefore tend to be below the levels that would reasonably be expected to be used to control these weeds and pests on an average farm. A good example to illustrate this relates to the US cotton crop where, for example, in 2008, nearly half of the conventional cotton crop was located in Texas. Here, levels of bollworm pests (the main target of biotech insect-resistant cotton) tend to be consistently low, and cotton farming systems are traditionally of an extensive, low input nature (e.g., the average cotton yield in Texas was about 82% of the US average in 2008).
- Some of the farms continuing to use conventional (non-biotech) seed traditionally use extensive, low-intensity production methods (including organic) in which limited (below average) use of pesticides is a feature (see, for example, the Texas cotton example above). The usage pattern of this subset of growers is therefore likely to understate usage for the majority of farmers if all crops were conventional.
- Many of the farmers using biotech traits have experienced improvements in pest and weed control from using this technology relative to the conventional control methods previously used. If these farmers were to now switch back to using conventional techniques—based wholly on pesticides—it is likely that most would wish to maintain the levels of pest/weed control delivered with use of the biotech traits and therefore would use higher levels of pesticide than they did in the pre-biotech crop days.

To overcome these problems in the analysis of pesticide use changes arising from the adoption of biotech crops (i.e., where biotech traits account for the majority of total plantings), presented in this article,[3] actual recorded usage levels for the biotech crops are used (based on survey data), with the conventional alternative (counterfactual situation) identified based on opinion from extension advisors and industry specialists as to what farmers might reasonably be expected to use in terms of crop protection practices and usage levels of pesticide.[4] This methodology has been used by others, for example Johnson and Strom (2007). Details of how this methodology has been applied to the 2008 calculations, sources used for each trait/country combination examined and examples of typical conventional versus biotech pesticide applications are provided in Appendices A and B.

The most common way in which changes in pesticide use with biotech crops has been presented in the literature has been in terms of the volume (quantity) of pesticide applied. While comparisons of total pesticide volume used in biotech and conventional crop production systems are a useful indicator of associated environmental impacts, amount of active ingredient used is an imperfect measure because it does not account for differences in the specific pest-control programs used in biotech and conventional cropping systems. For example, different specific products used in biotech 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.

In this article, the pesticide-related environmental impact changes associated with biotech crop adoption

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[3] *Also see earlier work by the authors (Brookes & Barfoot, 2006, 2007, 2008, 2009b).*

[4] *In other words, Brookes and Barfoot draw on the findings of work by various researchers at the National Center for Food and Agriculture Policy (Carpenter & Gianessi, 1999; Johnson & Strom, 2007; Sankula & Blumenthal, 2003, 2006; also see http://www.ncfap.org). This work consults with in excess of 50 extension advisors in almost all of the states growing corn, cotton, and soybeans and therefore provides a reasonably representative perspective on likely usage patterns.*

Table 1. Impact of changes in the use of herbicides and insecticides from growing biotech crops globally 1996-2008.

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 on biotech crops	% change in environmental impact associated with herbicide & insecticide use on biotech crops	Area biotech trait 2008 (million ha)
GM HT soybeans	-50.45	-5,314.8	-3.0	-16.6	62.47
GM HT maize	-111.58	-2,724.2	-7.5	-8.5	22.40
GM HT canola	-13.74	-437.2	-17.6	-24.3	5.83
GM HT cotton	-6.29	-188.4	-3.4	-5.5	2.41
GM IR maize	-29.89	-1,007.0	-35.3	-29.4	36.04
GM IR cotton	-140.6	-6,555.7	-21.9	-24.8	13.20
GM HT sugar beet	+0.13	-0.46	+10	-2	0.26
Totals	**-352.42**	**-16,227.76**	**-8.4**	**-16.3**	**142.61**

are examined in terms of changes in the volume (amount) of active ingredient applied but supplemented by the use of an alternative indicator, developed at Cornell University in the 1990s: the environmental impact quotient (EIQ). The EIQ indicator, developed by Kovach, Petzoldt, and Degni, and Tette (1992) and updated annually, effectively integrates the various environmental impacts of individual pesticides into a single ‘field value per hectare.’ The EIQ value is multiplied by the amount of pesticide active ingredient (ai) used per hectare to produce a field EIQ value. For example, the EIQ rating for glyphosate is 15.33. By using this rating multiplied by the amount of glyphosate used per hectare (e.g., a hypothetical example of 1.1 kg applied per ha), the field EIQ value for glyphosate would be equivalent to 16.86/ha.

The EIQ indicator used is therefore a comparison of the field EIQ/ha for conventional versus biotech 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 (biotech versus conventional). The use of environmental indicators is commonly used by researchers, and the EIQ indicator has been, for example, cited by Brimner, Gallivan, and Stephenson (2004)—in a study comparing the environmental impacts of biotech and conventional canola—and by Kleiter et al. (2005).

The EIQ indicator provides an improved assessment of the impact of biotech crops on the environment when compared to only examining changes in volume of active ingredient applied, because it draws on some of the key toxicity and environmental exposure data related to individual products, as applicable to impacts on farm workers, consumers, and ecology. Readers should, however, note that the EIQ is an indicator only and does not take into account all environmental issues and impacts. It is therefore not a comprehensive indicator. Detailed examples of the relevant amounts of active ingredient used and their associated field EIQ values for biotech versus conventional crops for the year 2008 are presented in Appendix B.

Results

Biotech traits have contributed to a significant reduction in the environmental impact associated with insecticide and herbicide use on the areas devoted to biotech crops (Table 1). Since 1996, the use of pesticides on the biotech crop area was reduced by 352 million kg of active ingredient (8.4% reduction), and the environmental impact associated with herbicide and insecticide use on these crops—as measured by the EIQ indicator—fell by 16.3%. In absolute terms, the largest environmental gain has been associated with the adoption of GM IR cotton and reflects the significant reduction in insecticide use that the technology has allowed, in what has traditionally been an intensive user of insecticides. The volume of herbicides used in biotech soybean crops also decreased by 50 million kg (1996-2008), a 3% reduction, while the overall environmental impact associated with herbicide use on these crops decreased by a significantly larger 16.6%. This highlights the switch in herbicides used with most GM HT crops to active ingredients with a more environmentally benign profile than the ones generally used on conventional crops.

Important environmental gains have also arisen in the maize and canola sectors. In the maize sector, herbicide and insecticide use decreased by 141.5 million kg and the associated environmental impact of pesticide use on this crop area decreased due to a combination of reduced insecticide use (29.4%) and a switch to more environmentally benign herbicides (8.5%). In the canola sector, farmers reduced herbicide use by 13.7 million kg (a 17.6% reduction) and the associated environmental

Table 2. Biotech crop environmental benefits from lower insecticide and herbicide use 1996-2008: Developing versus developed countries.

	Change in field EIQ impact (in terms of million field EIQ/ha units): Developed countries	Change in field EIQ impact (in terms of million field EIQ/ha units): Developing countries
GM HT soybeans	3,692.8	1,622.0
GM HT maize	2,674.9	49.3
GM HT cotton	153.5	34.9
GM HT canola	437.2	0
GM IR corn	983.8	23.2
GM IR cotton	443.3	6,112.4
GM HT sugar beet	0.46	0
Total	**8,385.96**	**7,841.8**

impact of herbicide use on this crop area fell by 24.3% due to a switch to more environmentally benign herbicides.

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 2 shows roughly a 50% split of the environmental benefits (1996-2008) in developed and developing countries. Three quarters of the environmental gains in developing countries have been from the use of GM IR cotton.

Impact on Greenhouse Gas Emissions

Methodology

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 biotech crops and their impact on both fuel use and tillage systems. Reductions in the level of GHG emissions associated with the adoption of biotech crops is acknowledged in a wide body of literature (CTIC, 2002; Fabrizzi, Morónc, & García, 2003; Jasa, 2002; Johnson et al., 2005; Lazarus & Selley, 2005; Liebig et al., 2005; Reicosky, 1995; Robertson, Paul, & Harwood, 2000; West & Post, 2002). First, biotech 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, 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 with the number of spray applications of herbicides remaining the same for conventional production systems.[5]

In addition, there has been a shift from conventional tillage to reduced/no till. This has had a marked impact on tractor fuel consumption due to energy-intensive cultivation methods being replaced with no/reduced tillage and herbicide-based weed control systems. The GM HT crop where 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.[6] Before the introduction of GM HT soybean cultivars, no-tillage (NT) 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 NT systems 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 NT soybean area in the United States (also more than a five-fold increase in Argentina). In both countries, GM HT soybeans are estimated to account for more than 95% of the NT soybean crop area in 2007/8.

Substantial growth in NT production systems have also occurred in Canada, where the NT canola area increased from 0.8 million ha to 2.6 million ha (equal to about half of the total canola area) between 1996 and 2005 (95% of the NT canola area is planted with GM HT cultivars). Similarly the area planted to NT 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) and has remained at this share of the total crop in 2007 and 2008.

The fuel savings resulting from changes in tillage systems used in this article are drawn from estimates from studies by Jasa (2002), CTIC (2002), and the University of Illinois (2006). The adoption of NT farming systems is estimated to reduce cultivation fuel usage by 32.3 liters/ha compared with traditional conventional

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[5] *Evidence from different countries varies, with some countries exhibiting on average no change and others showing a small net reduction in the number of spray runs.*

[6] *See, for example, CTIC (2002) and American Soybean Association (2001).*

tillage (CT; which has an average usage of 43.7 liters/ha) and by 19.33 liters/ha compared with (the average of) reduced tillage (RT) cultivation methods (which has an average usage of 30.72 liters/ha). In turn, this results in reductions of carbon dioxide emissions of 88.81 kg/ha for NT relative to CT and 35.66 kg/ha for RT relative to CT.[7]

Secondly, the use of 'no-till' and 'reduced-till' farming systems that utilize less ploughing 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 into the environment. Rates of carbon sequestration have been calculated for cropping systems using normal tillage and reduced tillage and these were incorporated in the 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 Intergovernmental Panel on Climate Change (IPCC, 2006) estimates that the conversion from conventional-tillage to no-tillage systems stores between 50 kg carbon/ha^{-1} yr and 1,300 kg carbon/ha^{-1} yr (average 300 kg carbon/ha^{-1} yr). In the analysis presented below, a conservative saving of 300 kg carbon/ha^{-1} yr was applied to all NT agriculture and 100 kg carbon/ha^{-1} yr was applied to RT agriculture. Where some countries aggregate their no- and reduced-till data (e.g., Argentina), the reduced-tillage saving value of 100 kg carbon/ha^{-1} yr was used. 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 separate analysis and reviews of farm income literature impacts by the authors (see Brookes & Barfoot, 2009a) 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).[8]

Results

Herbicide-tolerant Soybeans

The United States: Over the 1996-2008 period, the area of soybeans cultivated in the United States increased rapidly from 25.98 million ha to 30.21 million ha. Over the same period, the area planted using conventional tillage is estimated to have fallen by 21.3% (from 7.5 million ha to 5.9 million ha), while the area planted using NT has increased by 62.3% (from 7.7 million ha to 12.5 million ha).

The most rapid rate of adoption of the GM HT technology has been by growers using NT systems (GM HT cultivars accounting for an estimated 99% of total NT soybeans in 2008). This compares with conventional-tillage systems for soybeans, where GM HT cultivars account for about 79% of total conventional-tillage soybean plantings. The importance of GM HT soybeans in the adoption of a NT system has also been confirmed by an American Soybean Association study (ASA, 2001) of conservation tillage. This study found that the availability of GM HT soybeans has facilitated and encouraged farmers to implement reduced-tillage practices; a majority of growers surveyed indicated that GM HT soybean technology had been the factor of *greatest* influence in their adoption of RT practices.

Based on the soybean crop area planted by tillage system, type of seed planted (GM and conventional) and applying the fuel usage consumption rates referred to in the methodology section,[9] the total consumption of tractor fuel has increased by only 2.1% (15.9 million liters)—from 746.4 to 762.4 million liters (1996 to 2008)—while the area planted increased by 16.3%, some 4.3 million ha. Over the same period, the average fuel usage fell 12.2%—from 28.7 liters/ha to 25.2 liters/ha. A comparison of biotech versus conventional pro-

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[7] *Based on one-liter fuel results in a carbon dioxide saving of 2.75 kg/ha from Lazarus and Selly (2005).*

[8] *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. The no/reduced-tillage areas to which these soil carbon reductions were applied were limited to the increase in the area planted to no/reduced tillage in each country since GM HT technology has been commercially available. In this way, the authors have tried to avoid attributing no/reduced-tillage soil carbon sequestration gains to GM HT technology on cropping areas that were using no/reduced-tillage cultivation techniques before GM HT technology became available. Also, the development of the no-tillage soybean crops have not been attributed to the plantings of GM HT crops in Brazil due to the rapid development of this production system before GM HT soybean technology was permitted in 2003.*

[9] *Our estimates are based on the following average fuel consumption rates: NT 11.4 liter/ha, RT 30.73 liters/ha (the average of fuel consumption for chisel ploughing and disking) and conventional tillage 43.7 liters/ha.*

Table 3. US soybeans: Permanent reduction in tractor fuel consumption and CO_2 emissions 1996-2008.

	Annual reduction based on 1996 average (liters/ha)	Crop area (million ha)	Total fuel saving (million liters)	Carbon dioxide (million kg)
1996	0.0	26.0	0.0	0.00
1997	0.5	28.3	13.7	37.71
1998	1.0	29.1	28.2	77.60
1999	1.0	29.8	30.8	84.73
2000	1.1	30.1	33.1	90.95
2001	1.4	30.0	41.7	114.63
2002	1.7	29.5	49.7	136.70
2003	2.3	29.7	67.5	185.52
2004	2.9	30.3	86.6	238.05
2005	4.2	28.9	120.4	331.18
2006	5.5	30.6	167.5	460.67
2007	3.5	25.8	90.0	247.40
2008	3.5	30.2	105.5	290.20
Total			**834.7**	**2,295.3**

Assumption: Baseline fuel usage is the 1996 level of 28.7 liters/ha.

Table 4. US soybeans: Potential soil carbon sequestration (1996 to 2008).

	Total carbon sequestered (million kg)	Average (kg carbon/ha)
1996	2,640.96	101.7
1997	3,061.99	108.1
1998	3,337.46	114.5
1999	3,431.70	115.0
2000	3,482.75	115.5
2001	3,569.75	119.0
2002	3,619.85	122.5
2003	3,855.54	129.8
2004	4,148.86	137.0
2005	4,432.87	153.5
2006	5,194.42	170.0
2007	3,707.41	144.0
2008	4,348.85	144.0

duction systems shows that in 2008, the average tillage fuel consumption on the biotech planted area was 24.3 liters/ha compared to 36.5 liters/ha for the conventional crop (primarily because of differences in the share of NT plantings).

The cumulative permanent reduction in tillage fuel use in US soybeans is summarized in Table 3. This amounted to a reduction in tillage fuel usage of 834.7 million liters, which equates to a reduction in carbon dioxide emission of 2,295.3 million kg.

Based on the crop area planted by tillage system and type of seed planted (biotech and conventional) and using estimates of the soil carbon sequestered by tillage system for corn and soybeans in continuous rotation (the NT system is assumed to store 300 kg of carbon/ha/year, the RT system assumed to *store* 100 kg carbon/ha/year, and the CT system assumed to *release* 100 kg carbon/ha/year),[10] our estimates of total soil carbon sequestered are (Table 4):

- an increase of 1,707.9 million kg carbon/year (from 2,641 million kg in 1996 to 4,349 million kg carbon/year in 2008 due to increases in both crop area planted and the NT soybean area);
- the average level of carbon sequestered per ha increased by 42.3 kg carbon/ha/year (from 101.7 to 144 kg carbon/ha/year).

Cumulatively, since 1996 the increase in soil carbon due to the increase in NT and RT in US soybean production systems has been 10,370 million kg of carbon which, in terms of carbon dioxide emission equates to a saving of 38,057 million kg of carbon dioxide that would otherwise have been released into the atmosphere (Table 5). This estimate does not, however, take into consideration the potential loss in carbon sequestration that arises when some farmers return to conventional

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[10] *The actual rate of soil carbon sequestered by tillage system is, however dependent upon soil type, soil organic content, quantity, and type of crop residue, so these estimates are indicative averages.*

Table 5. US soybeans: Potential additional soil carbon sequestration attributable to NT/RT systems (1996 to 2008).

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total carbon sequestered (million kg)	Carbon dioxide (million kg)
1996	0.0	26.0	0.00	0.00
1997	6.4	28.3	181.93	667.69
1998	12.8	29.1	374.36	1,373.89
1999	13.4	29.8	398.45	1,462.32
2000	13.9	30.1	417.99	1,534.01
2001	17.4	30.0	521.04	1,912.23
2002	20.9	29.5	616.89	2,264.00
2003	28.1	29.7	835.71	3,067.05
2004	35.4	30.3	1,071.19	3,931.26
2005	51.8	28.9	1,497.10	5,494.36
2006	68.3	30.6	2,087.44	7,660.89
2007	42.3	25.8	1,089.62	3,998.89
2008	42.3	30.2	1,278.14	4,690.77
Total			**10,369.86**	**38,057.37**

Assumption: Carbon sequestration remains at the 1996 level of 101.7 kg carbon/ha/year.

Table 6. Argentine soybeans: Permanent reduction in tractor fuel consumption and reduction in CO_2 emissions.

	Annual reduction based on 1996 average of 35.8 (l/ha)	Crop area (million ha)	Total fuel saving million liters	Carbon dioxide (million kg)
1996	0.0	5.9	0.0	0.00
1997	1.1	6.4	7.2	19.90
1998	3.4	7.0	23.6	64.93
1999	7.9	8.2	64.8	178.21
2000	10.2	10.6	107.8	296.59
2001	10.2	11.5	117.1	322.12
2002	11.3	13.0	146.7	403.50
2003	11.3	13.5	152.8	420.16
2004	11.3	14.3	162.3	446.46
2005	12.4	15.2	189.2	520.38
2006	13.4	16.2	215.7	593.11
2007	13.4	16.6	221.5	609.10
2008	13.4	17.0	227.0	624.33
Total			**1,635.7**	**4,498.79**

Note: Based on 21.07 liters/ha for NT and RT and 43.7 liters/ha for CT.

tillage and therefore should be treated as a maximum potential rather than an achieved level.

Argentina: Since 1996, the area planted to soybeans in Argentina has increased by 188% (from 5.9 to 17 million ha). Over the same period, the area planted using NT and RT practices also increased by an estimated 672%, from 2.07 to 15.98 million ha, while the area planted using CT decreased 73%, from 3.8 to 1.02 million ha.

As in the United States, a key driver for the growth in NT soybean production has been the availability of GM HT soybean cultivars, which, in 2008, accounted for 97.8% of the total Argentine soybean area.

Between 1996 and 2008 total fuel consumption associated with soybean cultivation increased by an estimated 169.6 million liters (80.2%), from 211.6 to 381.2 million liters/year. However, during this period the average quantity of fuel used per ha fell 37.34% from 35.8 to 22.4 liters/ha, due predominantly to the widespread use of GM HT soybean cultivars and NT/RT systems. If the

Table 7. Argentine soybeans: Potential additional soil carbon sequestration (1996 to 2008).

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total carbon sequestered (million kg)	Carbon dioxide (million kg)
1996	0.0	5.9	0.0	0.00
1997	-0.9	6.4	-5.9	-21.57
1998	12.8	7.0	89.1	327.00
1999	52.8	8.2	432.0	1,585.47
2000	72.8	10.6	771.0	2,829.42
2001	72.8	11.5	837.3	3,073.07
2002	82.8	13.0	1,073.6	3,940.24
2003	82.8	13.5	1,118.0	4,102.96
2004	82.8	14.3	1,187.9	4,359.75
2005	92.8	15.2	1,410.8	5,177.47
2006	100.8	16.2	1,628.1	5,975.23
2007	100.8	16.6	1,672.0	6,136.31
2008	100.8	17.0	1,713.8	6,289.71
Total			**11,927.7**	**43,775.07**

Assumption: NT = +150 kg carbon/ha/yr; CT = -100 kg carbon/ha/yr.

proportion of NT/RT soybeans in 2008 (applicable to the total 2008 area planted) had remained at the 1996 level, an additional 1,635.9 million liters of fuel would have been used. At this level of fuel usage, an additional 4,498.79 million kg of carbon dioxide would have otherwise been released into the atmosphere (Table 6).

Applying a conservative estimate of soil carbon retention of 150 kg/carbon/ha/yr for NT/RT soybean cropping in Argentina (tillage data in Argentina does not differentiate between NT and RT), a cumulative total of 11,927.8 million kg of carbon—which equates to a saving of 43,775.1 million kg of carbon dioxide—has been retained in the soil that would otherwise have been released into the atmosphere (Table 7).

Paraguay and Uruguay: NT/RT systems have also become important in soybean production in both Paraguay and Uruguay, where the majority of production in both countries are reported by industry sources to use NT/RT systems.

Using the findings and assumptions applied to Argentina (see above), the savings in fuel consumption for soybean production between 1996 and 2008 (associated with changes in NT/RT systems, the adoption of GM HT technology and comparing the proportion of NT/RT soybeans in 2008 relative to the 1996 level) has possibly amounted to 195.9 million liters. At this level of fuel saving, the reduction in the level of carbon dioxide released into the atmosphere has probably been 538.7 million kg. Applying the same rate of soil carbon retention for NT/RT soybeans as Argentina, the cumulative increase in soil carbon since 1996—due to the increase in NT/RT in Paraguay and Uruguay soybean production systems—has been 2,163.2 million kg of carbon. In terms of carbon dioxide emission, this equates to a saving of 7,938.94 million kg of carbon dioxide that may otherwise have been released into the atmosphere.

Herbicide-tolerant Canola

The analysis presented below relates to Canada only and does not include the US GM HT canola crop. This reflects the lack of information about the level of NT/RT in the US canola crop. Also, the area devoted to GM HT canola in the United States is relatively small by comparison to the corresponding area in Canada (0.39 million ha in the United States in 2008 compared to 5.4 million ha in Canada).

Since 1996 the cumulative permanent reduction in tillage fuel use in Canadian canola is estimated at 347.5 million liters, which equates to reduction in carbon dioxide emission of 955.39 million kg (Table 8).

In terms of the increase in soil carbon associated with the increase in NT and RT in Canadian canola production, the estimated values are summarized in Table 9. The cumulative increase in soil carbon equals 3,227 million kg of carbon, which in terms of carbon dioxide emission equates to a saving of 11,842 million kg of carbon dioxide that would otherwise have been released into the atmosphere.

Table 8. Canadian canola: Permanent reduction in tractor fuel consumption and CO_2 emissions 1996-2008.

	Annual reduction based on 1996 average 35.6 (l/ha)	Crop area (million ha)	Total fuel saving (million liters)	Carbon dioxide (million kg)
1996	0.0	3.5	0.0	0.00
1997	1.6	4.9	7.9	21.63
1998	1.6	5.4	8.8	24.11
1999	1.6	5.6	9.0	24.71
2000	1.6	4.9	7.8	21.58
2001	3.2	3.8	12.2	33.62
2002	4.8	3.3	15.8	43.46
2003	6.5	4.7	30.3	83.30
2004	8.1	4.9	39.9	109.68
2005	8.1	5.5	44.3	121.93
2006	9.7	5.2	50.8	139.59
2007	9.7	5.9	57.3	157.51
2008	10.3	6.5	63.4	174.27
Total			**347.5**	**955.39**

Note: Fuel usage NT = 11.4 liters/ha; CT = 43.7 liters/ha.

Table 9. Canada canola: Potential additional soil carbon sequestration (1996 to 2008).

	Annual increase in carbon sequestered based on 1996 average (kg carbon/ha)	Crop area (million ha)	Total carbon sequestered (million kg)	Carbon dioxide (million kg)
1996	0.0	3.5	0.0	0.00
1997	15.0	4.9	73.1	268.09
1998	15.0	5.4	81.4	298.86
1999	15.0	5.6	83.5	306.31
2000	15.0	4.9	72.9	267.50
2001	30.0	3.8	113.6	416.75
2002	45.0	3.3	146.8	538.67
2003	60.0	4.7	281.4	1,032.56
2004	75.0	4.9	370.4	1,359.46
2005	75.0	5.5	411.8	1,511.40
2006	90.0	5.2	471.4	1,730.21
2007	90.0	5.9	532.0	1,952.39
2008	95.9	6.5	588.6	2,160.16
Total			**3,226.9**	**11,842.36**

Note: NT/RT = +200 kg carbon/ha/yr; CT = -100 kg carbon/ha/yr.

Herbicide-tolerant Cotton and Maize

The contribution to reduced levels of carbon release arising from the adoption of GM HT maize and cotton is likely to have been marginal, and hence no assessments are presented. This conclusion is based on the following.

- Although the area of NT/RT cotton has increased significantly in countries such as the United States, it still only represented an estimated 21%[11] of the total cotton crop in 2007.
- As the soybean-maize rotation system is commonplace in the United States, the benefits of switching to a NT system have largely been examined above for soybeans.
- No significant changes to the average number of spray runs under a GM HT production system rel-

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[11] *Source: Conservation Technology Information Center, National Crop Residue, Management Survey (2007a, 2007b).*

Table 10. Permanent reduction in global tractor fuel consumption and CO_2 emissions resulting from the cultivation of GM IR cotton 1996-2008.

	Total cotton area in GM IR growing countries excluding India and China (million ha)	GM IR area (million ha) excluding India and China	Total spray runs saved (million ha)	Fuel saving (million liters)	CO2 emissions saved (million kg)
1996	7.49	0.86	3.45	3.60	9.91
1997	7.09	0.92	3.67	3.84	10.56
1998	7.24	1.05	4.20	4.39	12.08
1999	7.46	2.11	8.44	8.82	24.25
2000	7.34	2.43	9.72	10.16	27.94
2001	7.29	2.55	10.19	10.65	29.28
2002	6.36	2.18	8.71	9.10	25.04
2003	5.34	2.19	8.74	9.14	25.13
2004	6.03	2.80	11.20	11.70	32.18
2005	6.34	3.22	12.88	13.46	37.02
2006	7.90	3.94	15.75	16.46	45.27
2007	6.07	3.25	13.00	13.59	37.37
2008	4.99	2.41	9.65	10.08	27.72
Total			**119.60**	**124.99**	**343.75**

Note: Assumptions: 4 tractor passes per ha; 1.045 liters/ha of fuel per insecticide application.

ative to a conventional production system have been reported.

Insect-resistant Cotton

The cultivation of GM IR cotton has resulted in a significant reduction in the number of insecticide spray applications (e.g., Gianessi & Carpenter, 1999). During the period 1996 to 2008, the global cotton area planted with GM IR cultivars (excluding China and India)[12] has increased from 0.86 million ha to 3.94 million ha in 2006 before falling back to 2.41 million ha in 2008.[13] Based on a conservative estimate of four fewer insecticide sprays being required for the cultivation of GM IR cotton relative to conventional cotton and applying this to the global area (excluding China and India) of GM IR cotton over the period 1996-2008 suggests that there has been a reduction of 119.6 million ha of cotton being sprayed. The cumulative saving in tractor fuel consumption has been 124.99 million liters. This represents a permanent reduction in carbon dioxide emissions of 344 million kg (Table 10).

Insect-resistant Maize

No analysis of the possible contribution to reduced level of carbon sequestration from the adoption of GM IR maize (via fewer insecticide spray runs) and the adoption of corn rootworm (CRW) resistant maize is presented. This is because the impact of using these technologies on carbon sequestration is likely to have been small for the following reasons.

- In some countries (e.g., Argentina), insecticide use for the control of pests such as the corn borer has traditionally been negligible.
- Even in countries where insecticide use for the control of corn-boring pests has been practiced (e.g., the United States), the share of the total crop treated has been fairly low (under 10% of the crop) and varies by region and year according to pest pressure.
- Nominal application savings have occurred in relation to the adoption of GM CRW maize where more than 13.7 million ha were planted in 2008. The adoption of the GM CRW may become increasingly important with wider adoption of NT cultivation systems due to the potential increase in soil-borne pests.

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[12] *These are excluded because all spraying in these two countries is assumed to be undertaken by hand.*

[13] *This is in line with the general fall in total cotton plantings.*

Table 11. Summary of carbon sequestration impact 1996-2008.

Crop/trait/country	Permanent fuel saving (million liters)	Potential additional carbon dioxide saving from fuel saving (million kg)	Potential additional carbon dioxide saving from soil carbon sequestration (million kg)
US: GM HT soybeans	835	2,295	38,057
Argentina: GM HT soybeans	1,636	4,499	43,775
Other countries: GM HT soybeans	196	539	7,939
Canada: GM HT canola	347	955	11,842
Global GM IR cotton	125	344	0
Total	3,139	8,632	101,613

Note: Other countries: GM HT soybeans Paraguay and Uruguay (applying US carbon sequestration assumptions). Brazil not included because of NT/RT adoption largely in the absence of GM HT technology.

Discussion and Conclusions

The analysis of pesticide use changes arising from the adoption of biotech crops shows that there have been important environmental benefits, amounting to 352 million kg less pesticide use by growers (an 8.4% reduction in the amount of active ingredient applied). As weight of active ingredient applied is a fairly crude measure of environmental impact, the analysis considered impacts using an alternative (more rounded) measure, known as the EIQ. Based on this, the environmental benefits have been more significant at a 16.3% reduction in the environmental impact associated with insecticide and herbicide use on the global crop area planted to biotech traits (1996-2008). The most significant environmental benefits derived have been associated with the adoption of GM IR cotton, which has resulted in a substantial reduction in insecticide applications on cotton. There have also been important environmental gains associated with the adoption of GM HT technology, which has seen a switch to the use of more environmentally benign active ingredients.

The analysis also shows that biotechnology trait adoption has made important contributions to reducing GHG emissions associated with cropping agriculture, and a summary of the total carbon sequestration impact of GM crops is presented in Table 11. This shows that the permanent savings in carbon dioxide emissions (arising from reduced fuel use of 3,137 million liters of fuel) since 1996 have been about 8,632 million kg and the additional amount of soil carbon sequestered since 1996 has been equivalent to 101,613 million tonnes of carbon dioxide that has not been released into the global atmosphere.[14] The reader should, however, note that these soil carbon savings are based on saving arising from the rapid adoption of NT/RT farming systems in North and South America for which the availability of GM HT technology has been cited by many farmers as an important facilitator. GM HT technology has therefore probably been an important contributor to this increase in soil carbon sequestration but is not the only factor of influence. Other influences, such as the availability of relatively cheap generic glyphosate (the real price of glyphosate fell threefold between 1995 and 2000 once patent protection for the product expired), have also been important, as illustrated by the rapid adoption of NT/RT production systems in the Brazilian soybean sector, largely in the absence of the GM HT technology.[15] Cumulatively the amount of carbon sequestered may be higher than these estimates due to year-on-year benefits to soil quality; however, equally with only an estimated 15-25% of the crop area in continuous NT systems, it is likely that the total cumulative soil sequestration gains have been lower. Nevertheless, it is not possible to estimate cumulative soil sequestration gains that take into account reversions to conventional tillage because of the lack of detailed, disaggregated farm- and field-level tillage data for the

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[14] *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 section of the report.*

[15] *The reader should note that the estimates of soil carbon sequestration savings presented do not include any for soybeans in Brazil because we have assumed that the increase in NT/RT area has not been primarily related to the availability of GM HT technology in Brazil.*

Table 12. Context of carbon sequestration impact 2008: 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	290	129	4,691	2,085
Argentina: GM HT soybeans	624	277	6,290	2,795
Other countries: GM HT soybeans	82	37	1,214	539
Canada: GM HT canola	179	80	2,223	988
Global GM IR cotton	28	12	0	0
Total	1,205	534	14,417	6,408

Note: Assumption: 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.

1996-2008 period. Consequently, the estimate provided above of 101,613 million tonnes of carbon dioxide not released into the atmosphere should be treated with caution and clearly represents a potential maximum rather than a realized level.

Further examining the context of the carbon sequestration benefits, Table 12 shows the carbon dioxide equivalent savings associated with planting of biotech crops for the latest year (2008) in terms of the number of car-use equivalents. This shows that in 2008, the permanent carbon dioxide savings from reduced fuel use was the equivalent of removing nearly 0.534 million cars from the road for a year, and the additional soil carbon sequestration gains were equivalent to removing nearly 6.4 million cars from the roads. In total, biotech crop-related carbon dioxide emission savings in 2008 were equal to the removal from the roads of nearly 6.9 million cars, equal to about 26% of all registered private cars in the United Kingdom.

The impacts identified in this article are, however, probably conservative, reflecting the limited availability of relevant data and conservative assumptions used. In addition, the analysis examines only a limited number of environmental indicators. As such, subsequent research of the environmental impact might usefully include additional environmental indicators such as impact on soil erosion.

References

American Soybean Association. (2001). *Conservation tillage study.* St. Louis, MO: Author. Available on the World Wide Web at: http://soygrowers.com/ctstudy/ctstudy_files/frame.htm.

Asia-Pacific Consortium on Agricultural Biotechnology (APCoAB). (2006). *Bt cotton in India: A status report*. New Delhi, India: ICRASTAT.

Brimner, T.A., Gallivan, G.J., & Stephenson, G.R. (2004). Influence of herbicide-resistant canola on the environmental impact of weed management. *Pest Management Science, 61*(1), 47-52.

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

Brookes, G. (2005). *The farm-level impact of herbicide-tolerant soybeans in Romania*. *AgBioForum, 8*(4), 235-241. Available on the World Wide Web: http://www.agbioforum.org.

Brookes, G. (2008). The benefits of adopting GM insect resistant (Bt) maize in the EU: First results from 1998-2006. *International Journal of Biotechnology, 134*(3-4).

Brookes, G., & Barfoot, P. (2006). *Global impact of biotech crops: Socio-economic and environmental effects 1996-2004. AgBioForum*, *8*(2&3), 187-196. Available on the World Wide Web: http://www.agbioforum.org.

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

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

Brookes, G., & Barfoot, P. (2009a). *Global impact of biotech crops: Income and production effects 1996-2007. AgBioForum*, *12*(2), 184-201. Available on the World Wide Web: http://www.agbioforum.org.

Brookes, G., & Barfoot, P. (2009b). *Global impact of biotech crops: Socio-economic and environmental effects 1996-2007. Outlooks on Pest Management*, *20*(6), 258-264.

Canola Council of Canada. (2001). *An agronomic & economic assessment of transgenic canola*. Winnipeg: Author. Available on the World Wide Web: http://www.canola-council.org/research_transgenic.aspx.

Carpenter, J., & Gianessi, L. (2002). *Agricultural biotechnology: Updated benefit estimates*. Washington, DC: National Center for Food and Agriculture Policy (NCFAP). Available on the World Wide Web: http://www.ncfap.org/reports/biotech/updatedbenefits.pdf.

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

Conservation Technology Information Center (CTIC). (2002). *Conservation tillage and plant biotechnology: How new technologies can improve the environment by reducing the need to plow*. West Lafayette, IN: CTIC. Available on the World Wide Web: http://www.ctic.purdue.edu/CTIC/BiotechPaper.pdf.

CTIC. (2007a). *2006 crop residue management survey: A survey of tillage usage by crop and acres planted*. West Lafayette, IN: Author. Available on the World Wide Web: http://www.conservationinformation.org/pdf/2006CRMSurveySummaryLoRes.pdf.

CTIC. (2007b) *National crop residue management survey for 2007*. West Lafayette, IN: Author. Available on the Worldwide Web: http://www.conservationinformation.org.

Doyle, B., et al. (2003). *The performance of roundup ready cotton 2001-2002 in the Australian cotton sector.* Armidale, Australia: University of New England.

Fabrizzi, K.P., Morónc, A., & García, F.O. (2003). Soil carbon and nitrogen organic fractions in degraded vs non-degraded mollisols in Argentina. *Soil Science Society of America Journal, 67*, 1831-41.

Galveo, A. (2009). *Unpublished farm survey findings of impact of insect resistant cotton in Brazil*. Celeres, Brazil.

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

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

Gusta, M., Smyth, S.J., Belcher, K., Phillips, P.W.B., & Castle, D. (2009). *Changes in chemical toxicity following adoption of herbicide tolerant canola in Western Canada* (working paper). Saskatoon, Saskatchewan, Canada: University of Saskatchewan, College of Biotechnology.

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

Intergovernmental Panel on Climate Change (IPCC). (2006). *Generic methodologies applicable to multiple land-use categories* (Chapter 2). In *Guidelines for national greenhouse gas inventories: Agriculture, forestry and other land use* (Volume 4). Available on the Worldwide Web: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_02_Ch2_Generic.pdf.

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

Jasa, P. (2002). *Conservation tillage systems*. Lincoln, NE: University of Nebraska. Available on the World Wide Web: http://agecon.okstate.edu/isct/labranza/jasa/tillagesys.doc.

Johnson, J.M.F., Reicosky, D.C., Allmaras, R.R, Sauer, T.J., Venterea, R.T., & Dell, C.J. (2005). Greenhouse gas contributions and mitigation potential of agriculture in the central USA. *Soil Tillage Research*, *83*(1), 73-94.

Johnson, S., & Strom, S. (2007, February). *Quantification of the impacts on US agriculture of biotechnology-derived crops planted in 2006*. Washington, DC: NCFAP. Available on the Worldwide Web: http://www.ncfap.org.

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

Kovach, J., Petzoldt, C., Degni, J., & Tette, J. (1992). *A method to measure the environmental impact of pesticides*. New York's Food and Life Sciences Bulletin. Geneva, NY: NYS Agricultural Experiment Station, Cornell University. Available on the World Wide Web: http://www.nysipm.cornell.edu/publications/EIQ.html.

Lazarus, W., & Selley, R. (2005). *Farm machinery economic cost estimates for late 2005*. St. Paul, MN: University of Minnesota Extension Service. Available on the World Wide Web: http://www.apec.umn.edu/faculty/wlazarus/mf2005late.pdf.

Liebig, M.A., Morgan, J.A., Reeder, J.D., Ellert, B.H., Gollany, H.T., & Schuman, G.E. (2005). Greenhouse gas contributions and mitigation potential of agriculture practices in northwestern USA and western Canada. *Soil Tillage Research, 83*(1), 25-52.

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

Monsanto Comercial Mexico. (2005). *Official report to Mexican Ministry of Agriculture* (unpublished).

Monsanto Comercial Mexico. (2007). *Official report to Mexican Ministry of Agriculture of the 2006 crop* (unpublished).

Monsanto Comercial Mexico. (2008). *Official report to Mexican Ministry of Agriculture of the 2008 crop* (unpublished).

Ontario Ministry of Agriculture, Food, & Rural Affairs. (2002, November). *Guide to weed control* (Publication 75). Ontario, Canada: Author. Available on the World Wide Web: http://www.omafra.gov.on.ca/english/crops/pub75/pub75toc.htm.

Pray, C., Huang, J., Hu, R., & Rozelle, S. (2002). Five years of Bt cotton in China: The benefits continue. *The Plant Journal*, *31*(4), 423-430.

Qaim, M., & De Janvry, A. (2005). Bt cotton and pesticide use in Argentina: Economic and environmental effects. *Environment and Development Economics*, *10*, 179-200. Available on the World Wide Web: http://are.berkeley.edu/~sadoulet/papers/Argentina_EDE.pdf.

Qaim, M., & Traxler, G. (2002, July). *Roundup Ready soybeans in Argentina: Farm level, environmental, and welfare effects*. Paper presented at the 6th International ICABR Conference, Ravello, Italy.

Reicosky, D.C. (1995). *Conservation tillage and carbon cycling: Soil as a source or sink for carbon*. Davis, CA: University of California. Available on the World Wide Web: http://vric.ucdavis.edu/issues/bulletinboard/soilconf/contill.pdf.

Robertson, G.P., Paul, E.A., & Harwood, R.R. (2000). Greenhouse gases in intensive agriculture: Contributions of individual gases to the radioactive forces of the atmosphere. *Science*, *289*, 1922-1925.

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

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

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

University of Illinois. (2006). *Costs and fuel use for alternative tillage systems*. *Farm Business Management*. Available on the Worldwide Web: http://www.farmdoc.illinois.edu/Manage/newsletters/fefo06_07/fefo06_07.html.

West, T.O., & Post, W.M. (2002). Soil Organic carbon sequestration rates by tillage and crop rotation: A global analysis. *Soil Science Society of American Journal*, *66*, 930-1046.

Appendix A: Details of Methodology as Applied to 2008 Calculations of Environmental Impact Associated with Pesticide Use Changes

Table A1. GM IR corn (targeting corn-boring pests) 2008.

Country	Area of trait (‘000 ha)	Maximum area treated for corn boring pests: Pre GM IR (‘000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use (‘000 kg)	Aggregate change in field EIQ/ha units
US	18,140	3,182	0.23	0.83	12.8	32.8	-1,909	-63.6
Canada	750	60.2	0.04	0.64	4.8	24.8	-36.12	-1.25
Argentina	1,150	0	0	0	0	0	0	0
Philippines	280	Very low - assumed zero	0	0	0	0	0	0
South Africa	1,668	1,768	0	0.094	0	3.42	-156.8	-5.71
Spain	79.3	36.3	0.36	1.32	0.9	26.9	-34.9	-0.94
Uruguay	110	Assumed to be zero: as Argentina	0	0	0	0	0	0
Brazil	1,450	Not known	Not known	Not known	Not known	Not known	None applied	None applied

Note: Brazil: *2008 was first year of use of GM IR corn technology. Insufficient data currently available to make an assessment.* Other countries: *Honduras and EU countries: Areas planted to GM IR corn under 10,000 ha in each country: not examined.*

Table A2. GM IR corn (targeting corn rootworm) 2008.

Country	Area of trait ('000 ha)	Maximum area treated for corn boring pests: Pre GM IR ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units
US	13,689	9,543	0.234	0.45	12.8	20.43	-2,063	-72.8

Note: There are no Canadian-specific data available. Analysis has therefore not been included for the Canadian crop of 119,000 ha planted to seed containing GM IR traits targeted at corn rootworm pests.

Table A3. GM IR cotton 2008.

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units
US	1,930	0.92	1.06	29.1	38.0	-276.6	-17.1
China	3,828	1.84	2.80	83.22	127.96	-3,675	-171.3
Australia	121.2	2.2	11.0	39	220	-1,066.9	-21.94
Mexico	70	3.6	5.22	120.4	177.0	-113.5	-3.96
Argentina	213	0.64	1.15	21.0	53.0	-108.6	-6.82
India	6,973	1.06	1.86	34.43	70.07	-5,565.1	-248.5
Brazil	170	0.64	1.15	21.0	53.0	-86.7	-5.44

Note: Due to the widespread and regular nature of bollworm and budworm pest problems in cotton crops, GM IR areas planted are assumed to be equal to the area traditionally receiving some form of conventional insecticide treatment.

South Africa (7,700 ha), Burkino Faso (8,500 ha), and Columbia (28,000 ha) not included in analysis due to lack of data and small size of plantings relative to total area of trait.

Brazil: due to a lack of data, usage patterns from Argentina have been assumed.

Table A4. GM HT soybeans 2008.

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units
US	27,790	1.63	1.62	26.29	36.16	+277.9	-274.3
Canada	880	1.32	1.43	20.88	34.20	-96.8	-11.73
Argentina	16,830	2.68	2.53	41.38	43.64	+2,524	-38.05
Brazil	13,320	2.37	1.94	36.34	32.96	+5,705	+45.0
Paraguay	2,430	1.16	0.99	18.8	20.05	+413.1	-3.04
South Africa	184	1.89	1.556	28.97	32.08	+61.4	-0.57
Uruguay	569	2.68	2.53	41.38	43.64	+85.4	-1.29
Mexico	7.3	1.62	1.76	24.83	41.02	-1	-0.12
Bolivia	454	1.16	0.99	18.8	20.05	+77.11	-0.57

Note: Due to lack of country-specific data, usage patterns in Paraguay assumed for Bolivia and usage in Argentina assumed for Uruguay.

Table A5. GM HT corn 2008.

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units
US glyphosate tolerant	18,847	2.06	3.48	43.08	77.15	-26,802	-642.0
US glufosinate tolerant	1,203	2.04	3.48	44.76	77.15	-1.738	-39.0
Canada glyphosate tolerant	477	1.83	2.71	37.01	61.10	-418.9	-11.44
Canada glufosinate tolerant	136	1.64	2.71	36.01	61.01	-145.3	-3.41
Argentina	805	2.36	2.77	43.80	57.82	-330.0	-11.3
South Africa	646	2.754	3.103	46.17	65.87	-225.3	-12.7

Note: The Philippines is not included due to lack of data on weed-control methods and product use.

Table A6. GM HT cotton 2008.

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units
US	2,082.8	2.83	3.26	50.6	60.08	-896	-19.74
South Africa	11.0	1.80	1.81	27.59	31.86	-0.11	-0.05
Australia	122.5	4.0	6.29	67.28	113.50	-281.4	-5.66
Argentina	210	1.80	3.48	27.60	68.04	-358.7	-8.6

Note: Mexico is not included due to lack of data on herbicide use.

Table A7. GM HT canola 2008.

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/HA GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units
US glyphosate tolerant	180.1	0.649	1.12	9.95	25.71	-84.8	-2.84
US glufosinate tolerant	200.1	0.383	1.12	7.78	25.71	-147.5	-3.59
Canada glyphosate tolerant	2,943	0.7	0.56	10.68	11.52	+403.2	-2.47
Canada glufosinate tolerant	2,681	0.35	0.56	7.07	11.52	-569.1	-11.93

Table A8. GM herbicide-tolerant sugar beet 2008.

Country	Area of trait ('000 ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units
US	258	1.90	1.40	29.13	30.89	+129	-0.45

Appendix B: Examples of EIQ Calculations

Table B1. Estimated typical herbicide regimes for conventional reduced/no till soybean production systems that will provide an equal level of weed control to the GM HT system in Argentina 2008.

	Active ingredient	Field eiq/ha
	Option 1	
Glyphosate	0.864	13.25
Metsulfuron	0.03	0.50
2 4 d amine	0.3	6.21
Imazethapyr	0.08	1.57
Diflufenican	0.05	0.88
Clethodim	0.144	2.45
Total	**1.468**	**24.85**
	Option 2	
Glyphosate	1.35	20.70
Dicamba	0.0576	1.46
Acetochlor	1.08	21.49
haloxifop *	0.096	2.13
Sulfentrazone	0.0875	1.02
Total	**2.67**	**46.80**
	Option 3	
Glyphosate	1.62	24.83
Atrazine	0.384	8.79
Bentazon	0.6	11.22
2 4 db ester	0.04	0.61
Imazaquin	0.024	0.37
Total	**2.67**	**45.83**
	Option 4	
Glyphosate	1.8	27.59
2 4 d amine	0.384	7.95
Flumetulam	0.06	0.94
Fomesafen	0.25	6.13
Chlorimuron	0.015	0.29
Fluazifop	0.12	3.44
Total	**2.63**	**46.34**
	Option 5	
Glyphosate	1.8	27.59
Metsulfuron	0.05	0.84
2 4 d amine	0.75	15.53
Imazethapyr	0.1	1.96
haloxifop	0.096	2.13
Total	**2.80**	**48.05**
	Option 6	
Glyphosate	1.8	27.59
Metsulfuron	0.05	0.84
2 4 d amine	0.75	15.53
Imazethapyr	0.1	1.96
Clethodim	0.24	4.08
Total	2.94	49.99
Average all	**2.53**	**43.64**

Sources: AAPRESID (Argentine No-Till Farmers Association, personal communication) and Monsanto Argentina (personal communications, 2006, 2007, & 2009).

Table B2. GM HT soybeans Argentina 2008.

	Active ingredient (kg/ha)	Field eiq/ ha value
Derived from AMIS Global farm survey market research data	2.68	41.38

Table B3. GM HT versus conventional corn Argentina 2008.

	Active ingredient (kg/ha)	Field eiq/ha value
Conventional		
	Option 1	
Acetechlor	1.68	33.43
Atrazine	1.0	22.90
Misotrione	0.14	2.52
Total	**2.82**	**58.85**
	Option 2	
Acetechlor	1.68	33.43
Atrazine	1.0	22.90
Foramsulam	0.03	0.46
Total	**2.71**	**56.79**
Average conventional	2.77	57.82
GM HT corn		
Acetochlor	0.84	16.72
Atrazine	0.5	11.45
Glyphosate	1.02	15.64
Total	**2.36**	**43.80**

Sources: AMIS Global and Monsanto Argentina (personal communication).

Table B4. Typical herbicide regimes for GM HT soybeans in South Africa.

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
Conventional soybeans		
	Option 1	
Alochlor	1.536	27.49
Chlorimuron	0.01	0.19
Total	**1.546**	**27.69**
	Option 2	
S Metalochlor	1.536	33.79
Imazethapyr	0.07	0.78
Total	**1.576**	**34.58**
	Option 3	
S Metalochlor	1.536	33.79
Chlorimuron	0.01	0.78
Total	1.546	34.58
Average	1.556	32.08
GM HT soybeans		
Glyphosate	1.89	28.97

Source: Monsanto South Africa (personal communication).

Table B5. Typical herbicide regimes for GM HT maize in Canada.

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
Conventional maize		
Metalochlor	1.3566	29.84
Atrazine	1.1912	27.28
Primsulfuron	0.0244	0.41
Dicamba	0.14	3.54
Total	**2.7122**	**61.07**
GM glyphosate-tolerant maize		
Metalochlor	0.678	14.92
Atrazine	0.594	13.60
Glyphosate	0.56	8.58
Total	**1.832**	**37.10**
GM glufosinate-tolerant maize		
Metalochlor	0.678	14.92
Atrazine	0.594	13.60
Glufosinate	0.37	7.49
Total	**1.642**	**36.01**

Sources: Ontario Ministry of Agriculture, Food, and Rural Affairs (2002), industry (personal communication with various seed industry sources).

Table B6. Typical insecticide regimes for cotton in India 2008.

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
Conventional cotton		
	Option 1	
Imidacloprid	0.0356	1.31
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.44
Diafenthiuron	0.1	2.53
Triazophos	0.5	17.80
Profenfos	0.625	37.19
Acephate	0.6	14.94
Spinosad	0.384	5.53
Metaflumizone	0.025	0.82
Flubendiamide	0.048	0.93
Total	**2.42**	**84.15**
	Option 2	
Imidacloprid	0.0356	1.31
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.44
Diafenthiuron	0.1	2.53
Profenfos	0.625	37.19
Chloripyrifos	0.4	10.76
Metaflumizone	0.025	0.82
Emamectin	0.011	0.29
Total	**1.30**	**56.00**
Average conventional	1.86	70.07
GM IR cotton		
Imidacloprid	0.0356	1.31
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.44
Diafenthiuron	0.1	2.53
Triazophos	0.5	17.80
Profenfos	0.625	37.19
Total	**1.36**	**61.92**
	Option 2	
Imidacloprid	0.0356	1.31
Thiomethoxam	0.05	1.67
Acetamiprid	0.05	1.44
Diafenthiuron	0.1	2.53
Total	**0.24**	**6.94**
Average GM IR cotton	1.06	34.43

Source: Monsanto India (personal communication).

Table B7. Data sources (for pesticide usage data).

	Sources of data for assumptions
US	Gianessi and Carpenter (1999) Carpenter and Gianessi (2002) Sankula and Blumenthal (2003, 2006) Johnson and Strom (2007) All of the above mainly for conventional regimes (based on surveys of extension advisors across the United States) DMR Kynetec—private market research data on pesticide usage. Is the most comprehensive dataset on crop pesticide usage at the farm level and allows for disaggregation to cover biotech versus conventional crops. This source primarily used for usage on biotech traits.
Argentina	AMIS Global—private market research data on pesticide use. Is the most detailed dataset on crop pesticide use. AAPRESID (farmer producers association)—personal communication (2007) Monsanto Argentina (personal communication, 2005, 2007, 2009) Qaim and De Janvry (2005) Qaim and Traxler (2002)
Brazil	AMIS Global Galveo (2009) and personal communication Monsanto Brazil (2008) Monsanto Brazil (personal communication, 2007, 2009)
Uruguay	As Argentina: No country-specific data identified
Paraguay	As Argentina for conventional soybeans (over-the-top usage), AMIS Global for GM HT soybeans
Bolivia	As Paraguay: No country-specific data identified
Canada	George Morris Centre (2004) Canola Council of Canada (2001) Gusta, Smyth, Belcher, Phillips, and Castle (2009) Ontario Ministry of Agriculture, Food, & Rural Affairs (2002 and updated annually)
South Africa	Monsanto South Africa (personal communication, 2005, 2007, 2009) Ismael, Bennett, Morse, and Buthelezi (2002)
Romania	Brookes (2005)
Australia	Doyle et al. (2003) Commonwealth Scientific and Industrial Research Organisation (CSIRO, 2005) Monsanto Australia (personal communication, 2005, 2007, 2009)
Spain	Brookes (2003, 2008)
China	Pray et al. (2002) Monsanto China (personal communication, 2007, 2009)
Mexico	Monsanto Comercial Mexico (2005, 2007, 2008) Traxler, Godoy-Avilla, Falck-Zepeda, and Espinoza-Arellano (2001)
India	Asia-Pacific Consortium on Agricultural Biotechnology (APCOAB, 2006) IMRB International (2007) Monsanto India (personal communication, 2007, 2008, 2009)