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Global impact of biotech crops
Environmental effects, 1996–2010

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This paper updates the assessment of the impact commercialized agricultural biotechnology is having on global agriculture, from some important environmental perspectives. 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 443 million kg (-9.1%) and, as a result, decreased the environmental impact associated with herbicide and insecticide use on these crops [as measured by the indicator the Environmental Impact Quotient (EIQ)] by 17.9%. The technology has also significantly reduced the release of greenhouse gas emissions from this cropping area, which, in 2010, was equivalent to removing 8.6 million cars from the roads.

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 analysis presented by the authors in Agbio Forum 8:187–196,[1] 9:1–13,[2] 11:21–38,[3] and 13:76–94 [4] and GM Crops 2011; 12:34–49.[5] As such, the methodology remains largely unchanged from previous papers on this subject by the authors, with the key differences between each year's paper being the provision of additional (one more year) and updated analysis. The authors undertake this updated analysis to provide interested readers with on-going and current assessments of some of the key environmental impacts associated with the global adoption of biotech crops. By doing so, it is hoped that the data and analysis presented will contribute to wider and greater understanding of the impact of this technology adoption in agriculture and facilitate more informed decision making relating to the use of the technology, especially in countries where crop biotechnology is currently not permitted.

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

The environmental impact analysis undertaken focuses on the following:

• The impacts associated with changes in the amount of insecticides and herbicides applied to the biotech crops relative to conventionally grown alternatives. Herbicides and insecticides are used to protect plants (crops) from pests and weeds and careful use of them can deliver important benefits for society, namely increasing the availability of good quality, reasonably priced foods and animal feed. However, insecticides and herbicides can, by their nature, be harmful to living organisms and therefore there are risks associated with their use. This means a balance has to be found relating to levels of use that contribute to delivering the important benefits referred to above while, at the same time, safeguarding human health, reducing contamination of water and reducing impacts on biodiversity. If biotech crops are better able to achieve this balance by delivering the same or higher levels of food production but with reduced risks to human health, of water contamination and to biodiversity, society benefits.

• The contribution of biotech crops toward reducing global greenhouse gas (GHG) emissions. It is widely accepted by governments around the world that increases in atmospheric levels of greenhouse gases due to human activity are detrimental to the global environment. Therefore if the adoption of crop biotechnology contributes to a reduction in the level of greenhouse gas emissions from agriculture, this represents a positive development for the world.

The analysis is mostly based on existing farm level impact data of biotech crops. Primary data for impacts of commercial biotech cultivation on both pesticide usage and greenhouse gas emissions are, however, limited and are not available for every crop, in every year and for each country. Nevertheless, all identified, representative, previous research has been utilized. This has been supplemented by the authors' own data collection and analysis. The analysis of pesticide usage also takes into consideration changes in the pattern of herbicide use in recent years that reflect measures taken by some farmers to address issues of weed resistance to the main herbicide (glyphosate) used with herbicide tolerant biotech crops.

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Table 1. Impact of changes in the use of herbicides and insecticides from growing biotech crops globally 1996–2010

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 and insecticide use on biotech crops	Area biotech trait 2010 (million ha)
GM herbicide tolerant soybeans	-34.2	-6,346.9	-1.7	-16.4	71.6
GM herbicide tolerant maize	-169.9	-4,199.2	- 10.0	-11.5	27.0
GM herbicide tolerant canola	-14.4	-478.6	-18.2	-27.6	6.7
GM herbicide tolerant cotton	-12.1	-347.6	-5.2	-8.1	4.9
GM insect resistant maize	-42.9	-1,571.5	-41.9	-37.7	34.1
GM insect resistant cotton	-170.5	-7,615.1	-23.9	-26.0	17.7
GM herbicide tolerant sugar beet	+0.54	-2.8	+19.0	-1.0	0.46
Totals	**-443.46**	**-20,561.7**	**-9.1**	**-17.9**	**162.46**

Results and Discussion

Results: environmental impacts of insecticide and herbicide use changes. 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 443 million kg of active ingredient (9.1% reduction), and the environmental impact associated with herbicide and insecticide use on these crops, as measured by the EIQ indicator, fell by 17.9%.

In absolute terms, the largest environmental gain has been associated with the adoption of GM insect resistant (IR) cotton (-23.9% reduction in the volume of active ingredient used and a 26% reduction in the EIQ indicator 1996–2010) 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 34 million kg (1996–2010), a 1.7% reduction, while the overall environmental impact associated with herbicide use on these crops decreased by a significantly larger 16.4%. This highlights the switch in herbicides used with most GM herbicide tolerant (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 212.8 million kg (1996–2010), and the associated environmental impact of pesticide use on this crop area decreased, due to a combination of reduced insecticide use (37.7%) and a switch to more environmentally benign herbicides (11.5%). In the canola sector, farmers reduced herbicide use by 14.4 million kg (a 18.2% reduction), and the associated environmental impact of herbicide use on this crop area fell by 27.6% (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 a 55%:45% split of the environmental benefits (1996–2010) respectively in developed (55%) and developing countries (45%). Over three-quarters (76%) of the environmental gains in developing countries have been from the use of GM IR cotton.

It should, however, be noted that in some regions where GM HT crops have been widely grown, some farmers have relied too much on the use of single herbicides like glyphosate to manage weeds in GM HT crops and this has contributed to the development of weed resistance. Worldwide, there are 21 weed species that are currently resistant to glyphosate[6] (compared with, for example, 69 weed species resistant to triazine herbicides such as atrazine). A few of the glyphosate resistant species, such as marestail (*Conyza canadensis*) and palmer pigweed (*Amaranthus palmeri*) are now reasonably widespread in the US, especially marestail, where there are several million acres infested and palmer pigweed, in Southern states, where over a million acres are estimated to exhibit such resistance. In Argentina, development of resistance to glyphosate in weeds such as Johnson Grass (*Sorghum halepense*) is also reported.

Where this has occurred, farmers have had to adopt reactive weed management strategies incorporating the use of a mix of herbicides. In recent years, there has also been a growing consensus among weed scientists of a need for changes in the weed management programs in GM HT crops because of the evolution of these weed populations that are resistant to glyphosate. While the

Table 2. Biotech crop environmental benefits from lower insecticide and herbicide use 1996–2010: developing vs. 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	-4,657.1	-1,689.8
GM HT maize	-4,076.7	-122.5
GM HT cotton	-274.9	-72.7
GM HT canola	-478.6	0
GM IR corn	-1,267.9	-303.6
GM IR cotton	-577.1	-7,038.0
GM HT sugar beet	-2.8	0
Total	**-11,335.1**	**-9,226.6**

Table 3. Carbon sequestration impacts 2010

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)
USA: GM HT soybeans	92.1	246	4,810
Argentina: GM HT soybeans	250.9	670	6,762
Brazil: GM HT soybeans	136.3	364	3,680
Bolivia, Paraguay, Uruguay: GM HT soybeans	68.5	183	1,850
Canada: GM HT canola	41.2	110	532
Global: GM IR cotton	24.0	64	0
Brazil: GM IR corn	29.2	78	0
Total	**642.2**	**1,715**	**17,634**

overall level of weed resistance in areas planted to GM HT crops is still relatively low (equal to between 5% and 10% of the total US cropping area annually planted to GM HT crops), growers of GM HT crops are increasingly being advised to be more proactive and include other herbicides in combination with glyphosate in their weed management systems even where instances of weed resistance to glyphosate have not been found. This is because proactive weed management programs generally require fewer herbicides and are more economical than reactive weed management programs. At the macro level, the adoption of both reactive and proactive weed management programs in GM HT crops has already begun to influence the mix, total amount and overall environmental profile of herbicides applied to GM HT soybeans, cotton, maize and canola and this is reflected in the data presented in this paper. For example, in the US GM HT soybean crop in 2010, just over a third of the crop received an additional herbicide treatment of one of the following active ingredients[a] 2 4 D, chlorimuron, clethodim and flumioxazin. This compares with 13% of the GM HT soybean crop receiving a treatment of one of these four herbicide active ingredients in 2006. As a result, the average amount of herbicide active ingredient applied to GM HT soybeans in the US (per hectare) has increased by about a third over the last five years (the associated EIQ value has increased by about 27%). This compares with the average amount of herbicide active ingredient applied to the conventional (non-GM) soybean alternative which increased by 15% over the same period (the associated EIQ value for conventional soybeans increased by 27%). The increase in the use of herbicides on conventional soybeans in the US can also be partly attributed to the ongoing development of weed resistance to herbicides commonly used and highlights that the development of weed resistance to herbicides is a problem faced by all farmers, regardless of production method.

Impact on greenhouse gas emissions. *Results.* The scope for biotech crops contributing to lower levels of GHG emissions comes from two principle sources:

(1) Reduced fuel use from less frequent herbicide or insecticide applications and a reduction in the energy use in soil cultivation. The fuel savings associated with making fewer spray runs (relative to conventional crops), and the switch to conservation, reduced and no-till farming systems, have resulted in permanent savings in carbon dioxide emissions. In 2010, this amounted to a saving of about 1,715 million kg of carbon dioxide, arising from reduced fuel use of 642.2 million liters (**Table 3**). The largest reductions in carbon dioxide emissions associated with reduced fuel use have come from the adoption of GM HT technology in soybeans (about 85% of total savings) and particularly in South America.

Over the period 1996 to 2010, the cumulative permanent reduction in fuel use has been about 12,232 million kg of carbon

a The four most used herbicide active ingredients used on soybeans after glyphosate (source: derived from GfK Kynetec).

Table 4. Summary of carbon sequestration impact 1996–2010

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)
USA: GM HT soybeans	798	2,130	42,577
Argentina: GM HT soybeans	1,841	4,916	49,652
Brazil: GM HT soybeans	952	2,542	25,674
Bolivia, Paraguay, Uruguay: GM HT soybeans	438	1,170	11,821
Canada: GM HT canola	302	806	3,915
Global: GM IR cotton	197	525	0
Brazil: GM IR corn	54	143	0
Total	**4,582**	**12,232**	**133,639**

dioxide, arising from reduced fuel use of 4,582 million liters (**Table 4**).

(2) The use of "no-till" and "reduced-till" farming systems. These production systems have increased significantly with the adoption of GM HT crops because the GM HT technology has improved growers ability to control competing weeds, reducing the need to rely on soil cultivation and seed-bed preparation as means to getting good levels of weed control. As a result, tractor fuel use for tillage is reduced, soil quality is enhanced and levels of soil erosion cut. In turn, more carbon remains in the soil and this leads to lower GHG emissions. Based on savings arising from the rapid adoption of no till/reduced tillage farming systems in North and South America, an extra 4,805 million kg of soil carbon is estimated to have been sequestered in 2010 (equivalent to 17,634 million tonnes of carbon dioxide that has not been released into the global atmosphere: **Table 3**).

The additional amount of soil carbon sequestered since 1996 has been equivalent to 133,639 million tonnes of carbon dioxide that has not been released into the global atmosphere.[b] The reader should note that these soil carbon savings are based on savings arising from the rapid adoption of NT/RT farming systems in North and South America (Argentina and Southern Brazil), for which the availability of GM HT technology, has been cited by many farmers as an important facilitator. GM HT technology has therefore probably been an important contributor to this increase in soil carbon sequestration, but is not the only factor of influence. Other influences such as the availability of relatively cheap generic glyphosate (the real price of glyphosate fell 3-fold between 1995 and 2000 once patent protection for the product expired) have also been important. Cumulatively, the amount of carbon sequestered may be higher than these estimates due to year-on-year benefits to soil quality (e.g., less soil erosion, greater water retention and reduced levels of nutrient run off). However, it is equally likely that the total cumulative soil sequestration gains have been lower because only a proportion of the crop area will have remained in NT/RT. It is, nevertheless, not possible to confidently estimate cumulative soil sequestration gains that take into account reversions to conventional tillage because of a lack of data. Consequently, the estimate provided of 133,639 million tons of carbon dioxide not released into the atmosphere (**Table 4**) should be treated with caution.

Placing these carbon sequestration benefits for 2010 within the context of the carbon emissions from cars, **Table 5** shows that:

• In 2010, the permanent carbon dioxide savings from reduced fuel use were the equivalent of removing 0.76 million cars from the road;

• The additional probable soil carbon sequestration gains in 2010 were equivalent to removing 7.84 million cars from the roads;

• In total, in 2010, the combined biotech crop-related carbon dioxide emission savings from reduced fuel use and additional soil carbon sequestration were equal to the removal from the roads of 8.6 million cars, equivalent to 27.7% of all registered cars in the UK;

• It is not possible to confidently estimate the probable soil carbon sequestration gains since 1996 (see above). If the entire biotech crop in reduced or no tillage[c] agriculture during the past 15 years had remained in permanent reduced/no tillage then this would have resulted in a carbon dioxide saving of 133,639 million kg, equivalent to taking 59.4 million cars off the road. This is, however, a maximum possibility and the actual levels of carbon dioxide reduction are likely to be lower.

Materials and Methods

Methodology: environmental impacts from insecticide and herbicide use changes. Assessment of the impact of biotech crops on insecticide and herbicide use requires comparisons of the

b These estimates are based on fairly conservative assumptions and therefore the true values could be higher. Also, some of the additional soil carbon sequestration gains from RT/NT systems may be lost if subsequent ploughing of the land occurs. Estimating the possible losses that may arise from subsequent ploughing would be complex and difficult to undertake. This factor should be taken into account when using the estimates presented in this paper.

c No-till farming means that the ground is not ploughed at all, while reduced tillage means that the ground is disturbed less than it would be with traditional tillage systems. For example, under a no-till farming system, soybean seeds are planted through the organic material that is left over from a previous crop such as corn, cotton or wheat.

Table 5. Context of carbon sequestration impact 2010: car equivalents

Crop/trait/country	Permanent carbon dioxide savings arising from reduced fuel use (million kg of carbon dioxide)	Permanent fuel savings: as average family car equivalents removed from the road for a year ('000s)	Potential additional soil carbon sequestration savings (million kg of carbon dioxide)	Soil carbon sequestration savings: as average family car equivalents removed from the road for a year ('000s)
USA: GM HT soybeans	246	109	4,810	2,138
Argentina: GM HT soybeans	670	298	6,762	3,005
Brazil: GM HT soybeans	364	162	3,680	1,636
Bolivia, Paraguay, Uruguay: GM HT soybeans	183	81	1,850	822
Canada: GM HT canola	110	49	532	237
Global: GM IR cotton	64	29	0	0
Brazil: GM IR corn	78	35	0	0
Total	**1,715**	**763**	**17,634**	**7,838**

Notes: Assumption: an average family car produces 150 g 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.

respective weed and pest control measures used on biotech vs. the "conventional alternative" form of production. This presents a number of challenges relating to availability and representativeness. Comparison data ideally derives from farm level surveys which collect usage data on the different forms of production. A search of 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[7–9] with even fewer,[10,11] providing data to the pesticide (active ingredient) level. Second, national level pesticide usage survey data are also extremely limited; in fact, there are no published 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 are 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 US.[d]

Unfortunately, even where national survey data are 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 US since the early 2000s), the conventional cropping data set used to identify pesticide use relates to a relatively small share of total crop area and therefore is likely to under estimate what usage would probably be in the absence of biotechnology. The reasons why this conventional cropping data set is unrepresentative of the levels of pesticide use that might reasonably be expected to be used in the absence of biotechnology include:

- 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. Therefore their pesticide usage levels tend to be below the levels that would reasonably be expected to control weeds and pests on an average farm. A good example to illustrate this relates to the US cotton crop where, for example, in 2010, 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 58% of the US average in 2010);
- Some of the farms continuing to use conventional (non-biotech) seed traditionally use extensive, low intensive production methods (including organic) in which limited (below average) use of pesticides is a feature (see the Texas cotton example above). The usage pattern of this sub-set of growers is therefore likely to understate usage for the majority of farmers if all crops were conventional;
- The widespread adoption of GM insect resistant technology has resulted in "area-wide" suppression of target pests such as the European corn borer in maize crops. As a result, conventional farmers (e.g., of maize in the US) have benefited from this lower level of pest infestation and the associated reduced need to conduct insecticide treatments;[18]
- Many of the farmers using biotech traits have experienced improvements in pest and weed control from using this

d 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 2010 and previous to this in 2005) and do not disaggregate usage by production type (biotech versus conventional).

technology relative to the conventional control methods previously used. If these farmers were now to switch back to using conventional techniques, it is possible that many might wish to maintain the levels of pest/weed control delivered with use of the biotech traits and therefore might use higher levels of pesticide than they did in the pre biotech crop days. This argument can, however, be countered by the constraining influence on farm level pesticide usage that comes from the cost of pesticides and their application. Ultimately, the decision to potentially use more pesticide or not would be made at the farm level according to individual assessment of the potential benefits (from higher yields) compared with the cost of additional pesticide use.

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 paper, 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.[e] This methodology has been used by others.[15] As an approach, this has an additional advantage of providing comparisons of current crop protection practices on both biotech crops and the conventional alternatives and so takes into account dynamic changes in crop protection management practices and technologies rather than making comparisons on past practices alone. Details of how this methodology has been applied to the 2010 calculations, sources used for each trait/country combination examined and examples of typical conventional vs. biotech pesticide applications are provided in **Supplemental Appendices 1 and 2**.

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 vs 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 paper, the pesticide related environmental impact changes associated with biotech crop adoption 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 et al. 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 vs. 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 vs. conventional). The use of environmental indicators is commonly used by researchers and the EIQ indicator has been, for example, cited by Brimner et al. in a study comparing the environmental impacts of biotech and conventional canola and by Kleiter.

The EIQ indicator provides an improved assessment of the impact of biotech crops on the environment when compared with examining only 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 vs conventional crops for the year 2010 are presented in **Supplemental Appendix 2**.

Methodology: impact of greenhouse gas emissions. The methodology used to assess impact on greenhouse gas emissions combines reviews of literature relating to changes in fuel and tillage systems and carbon emissions coupled with evidence from the development of relevant 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 are acknowledged in a wide body of literature.[20–27] 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. Lazarus[28] estimated that one pesticide spray application uses 1.31 liters of fuel which is equivalent to 3.5 kg/ha of carbon dioxide emissions.[f] 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 as for conventional production systems.[g]

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

e In other words Brookes & Barfoot draw on and update the findings of work by various researchers at the NCFAP[13,14]—see 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.

f In previous analysis by the authors 1.045 litres/ha was the fuel use estimate used [Lazarus & Selley (2005)[29]]. This has now been updated based on newer literature.[28]

g 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.

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.[h] Before the introduction of GM HT soybean cultivars, no tillage (NT) systems were practised by some farmers with varying degrees of success using a number of herbicides. 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 and cost advantages have contributed to the rapid adoption of GM HT cultivars and the near doubling of the NT soybean area in the US (also more than a 5-fold increase in Argentina). In both countries, GM HT soybeans are estimated to account for over 95% of the NT soybean crop area since 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 since 2007.

The fuel savings resulting from changes in tillage systems used in this paper are drawn from a review of literature including Jasa,[22] CTIC,[19] University of Illinois,[30] USDA Energy Estimator[31] and Reeder.[32] The adoption of no tillage (NT) farming systems is estimated to reduce cultivation fuel usage by 27.22 L/ha compared with traditional conventional tillage (CT: average usage 49.01 L/ha) and by 9.56 L/ha compared with (the average of) reduced tillage (RT) cultivation methods (average usage 39.45 L/ha). In turn, this results in reductions of carbon dioxide emissions of 72.68 kg/ha for NT relative to CT and 25.53 kg/ha for RT relative to CT.[i]

Second, 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 to the environment. A number of researchers have examined the relationship between carbon sequestration and different tillage systems.[24,25,27,33–41] This literature shows that the amount of carbon sequestered varies by soil type, cropping system, eco-region and tillage depth. It also shows that tillage systems can impact on levels of other GHG emissions such as methane and nitrous oxide and on crop yield. Overall, the literature highlights the difficulty in estimating the contribution NT/RT systems can make to soil carbon sequestration, especially because of the dynamic nature of soils, climate, cropping types and patterns. If a specific crop area is in continuous NT crop rotation, the full soil carbon sequestration benefits described in the literature can be realized. However, if the NT crop area is returned to a conventional tillage system, a proportion of the soil organic carbon gain will be lost. The temporary nature of this form of carbon storage will only become permanent when farmers adopt a continuous NT system which itself tends to be highly dependent upon effective herbicide-based weed control systems.

In sum, drawing on the various discussed literature, the analysis presented below uses the following conservative assumptions[j]:

• North America: soil carbon sequestered by tillage system for corn and soybeans in continuous rotation; NT systems store 375 kg of carbon/ha/year, RT systems store 175 kg carbon/ha/year; and CT systems release 25 kg carbon/ha/year;

• South America: soil carbon retained is 175 kg of carbon/ha/yr for NT/RT (soybean) cropping systems but CT systems release 25 kg carbon/ha/year[k];

• One kg of carbon sequestered is equivalent to 3.67 kg of carbon dioxide;

• Where the use of biotech crops has resulted in a reduction in the number of spray passes or the use of less intensive cultivation practices (i.e., less ploughing) this has provided (and continues to provide) a permanent reduction in carbon dioxide emissions.

These assumptions were applied to the reduced insecticide spray applications data on GM IR crops, derived from separate analysis and reviews of impact literature by the authors,[1,47] 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[l]). Additional detail relating to the estimates for carbon dioxide savings at the country and trait levels are presented in **Supplemental Appendix 3**.

Conclusions

During the past 15 years, the adoption of crop biotechnology by many farmers (15.4 million in 2010) has delivered important positive environmental contributions through its facilitation and evolution of environmentally friendly farming practices. More specifically:

h See for example, CTIC (2002)[19] and American Soybean Association (2001).[20]

i Based on 1 liter fuel results in a carbon dioxide saving of 2.67 kg/ha from Lazarus (2011).[23]

j In previous analysis, the authors have assumed NT systems store 300 kg of carbon/ha/y, RT systems store 100 kg of carbon/ha/y and CT systems release 100 kg of carbon/ha/y. The changes adopted in this paper reflect recent research referred to above. Readers should also note that the relative difference has remained unchanged at +400 kg and +200 kg of carbon/ha/y respectively. Similarly, for Argentina, the authors applied a carbon sequestration rate of 100 kg of carbon/ha/y for RT/NT systems and a carbon release of 100 kg of carbon/ha/y for CT systems, the difference between the systems has remained at 200 kg of carbon/ha/y in both the old and current analysis.

k As South American countries do not disaggregate data between no and reduced tillage areas, the more conservative carbon saving associated with reduced tillage is used.

l Due to the likely small scale impact and lack of tillage-specific data relating to GM HT cotton crops (and the US GM HT canola crop), analysis of possible GHG emission reductions in these crops have not been included. Also, no analysis is presented for no tillage used with GM HT maize because of the scope for "double counting" impacts where the crop is grown in rotation with GM HT soybeans.

• The environmental gains from the biotech IR traits have mostly been delivered directly by the technology through decreased use of insecticides;

• The gains from biotech HT traits have come from a combination of effects. In terms of the environmental impact associated with herbicide use, important changes in the profile of herbicides used have occurred (in favor of more environmentally benign products). Second, biotech HT technology has facilitated changes in farming systems. Thus, biotech HT technology (especially in soybeans) has played an important role in enabling farmers to capitalise on the availability of a low cost, broad-spectrum herbicide (glyphosate) and in turn, facilitated the move away from conventional to low/no-tillage production systems in both North and South America. This change in production system has delivered important environmental benefits, notably reduced levels of GHG emissions (from reduced tractor fuel use and additional soil carbon sequestration).

In relation to biotech HT crops, however, over reliance on the use of glyphosate by some farmers, in some regions, has contributed to the development of weed resistance. As a result, farmers are increasingly adopting a mix of reactive and proactive weed management strategies incorporating a mix of herbicides. Despite this, the overall environmental gains arising from the use of biotech crops have been, and continue to be, substantial.

The impacts identified in this paper 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.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Supplemental Material

Supplemental materials may be found here:
www.landesbioscience.com/journals/gmcrops/article/20061/

References

1. Brookes G, Barfoot P. Global impact of biotech crops: socio-economic and environmental effects 1996–2004, AgbioForum 2006; 8:187-96; http://www.agbioforum.org.
2. Brookes G, Barfoot P. Global impact of biotech crops: socio-economic and environmental effects 1996–2005, Agbioforum 2007; 9:1-13; http://www.agbioforum.org.
3. Brookes G, Barfoot P. Global impact of biotech crops: socio-economic and environmental effects 1996–2006, Agbioforum 2008; 11:21-38; http://www.agbioforum.org.
4. Brookes G, Barfoot P. Global impact of biotech crops: environmental effects 1996–2008, AgBioforum 2010; 13:76-94; http://www.agbioforum.org.
5. Brookes G, Barfoot P. Global impact of biotech crops: environmental effects 1996–2009. GM Crops 2011; 2:34-49; PMID:21844697; http://dx.doi.org/10.4161/gmcr.2.1.15529.
6. Weedscience; www.weedscience.org.
7. Qaim M, De Janvry A. Bt cotton and pesticide use in Argentina: economic and environmental effects. Environ Dev Econ 2005; 10:179-200; http://dx.doi.org/10.1017/S1355770X04001883.
8. Qaim M. Traxler G Roundup Ready soybeans in Argentina: farm level, environmental and welfare effects, 6th ICABR conference 2002. Ravello, Italy.
9. Pray CE, Huang J, Hu R, Rozelle S. Five years of Bt cotton in China—the benefits continue. Plant J 2002; 31:423-30; PMID:12182701; http://dx.doi.org/10.1046/j.1365-313X.2002.01401.x.
10. Brookes G. The farm level impact of using Bt maize in Spain. Paper presented at the 6th International Consortium on Agricultural Biotechnology Research (ICABR) Conference, Ravello, Italy 2003; http://www.pgeconomics.co.uk/pdf/bt_maize_in_spain.pdf.
11. Brookes G. The farm-level impact of herbicide-tolerant soybeans in Romania. AgBio Forum 2005; 8:235-41; http://www.agbioforum.org.
12. Hutchison WD, Burkness EC, Mitchell PD, Moon RD, Leslie TW, Fleischer SJ, Abrahamson M, et al. Areawide suppression of European Corn Borer with Bt maize reaps savings to non-bt maize growers. Science 2010; 330:222-5; www.sciencemag.org.
13. Sankula S, Blumenthal E. Impacts on US agriculture of biotechnology-derived crops planted in 2003: An update of eleven case studies. Washington, DC: NCFAP 2003; http://www.ncfap.org.
14. Sankula S, Blumenthal E. Impacts on US agriculture of biotechnology-derived crops planted in 2005: An update of eleven case studies. Washington, DC: NCFAP 2006; http://www.ncfap.org.
15. Johnson S, Strom S. Quantification of the impacts on US agriculture of biotechnology-derived crops planted in 2006. Washington, DC: National Center for Food and Agricultural Policy (NCFAP) 2007; http://www.ncfap.org.
16. Kovach J, Petzoldt C, Degni J, Tette J. A method to measure the environmental impact of pesticides. New York's Food and Life Sciences Bulletin. NYS Agriculture. Exp. Sta. Cornell University, Geneva NY 1992; 139:8 and annually updated; http://www.nysipm.cornell.edu/publications/EIQ.html.
17. Brimner TA, Gallivan GJ, Stephenson GR. Influence of herbicide-resistant canola on the environmental impact of weed management. Pest Manag Sci 2005; 61:47-52; PMID:15593073; http://dx.doi.org/10.1002/ps.967.
18. Kleiter G. The effect of the cultivation of GM crops on the use of pesticides and the impact thereof on the environment, RIKILT, Institute of Food Safety, Wageningen, Netherlands 2005.
19. Conservation Tillage and Plant Biotechnology (CTIC). How new technologies can improve the environment by reducing the need to plough 2002; http://www.ctic.purdue.edu/CTIC/Biotech.html.
20. American Soybean Association Conservation Tillage Study 2001; http://soygrowers.com/ctstudy/ctstudy_files/frame.htm.
21. Fabrizzi K, Moron A, Garan F. Soil Carbon and Nitrogen Organic Fractions in Degraded VS Non-Degraded Mollisols in Argentina. Soil Sci Soc Am J 2003; 67:1831-41; http://dx.doi.org/10.2136/sssaj2003.1831.
22. Jasa P. Conservation Tillage Systems, Extension Engineer, University of Nebraska 2002.
23. Reicosky D. Conservation tillage and carbon cycling: soil as a source or sink for carbon. University of Davis USA 1995.
24. Robertson GP, Paul EA, Harwood RR. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 2000; 289:1922-5; PMID:10988070; http://dx.doi.org/10.1126/science.289.5486.1922.
25. Johnson JMF, Reicosky DC, Allmaras RR, Sauer TJ, Venterea RT, Dell CJ. Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil Tillage Res 2005; 83:73-94; http://dx.doi.org/10.1016/j.still.2005.02.010.
26. Leibig MA, Morgan JA, Reeder JD, Ellert BH, Gollany HT, Schuman GE. Greenhouse gas contributions and mitigation potential of agriculture practices in north-western USA and western Canada. Soil Tillage Res 2005; 83:25-52; http://dx.doi.org/10.1016/j.still.2005.02.008.
27. West T, Post W. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Analysis. Soil Sci Soc Am J 2002; 66:1930-46; http://dx.doi.org/10.2136/sssaj2002.1930.
28. Lazarus WF. Machinery Cost Estimates May 2011, University of Minnesota Extension Service 2011.
29. Lazarus W, Selley R. Farm Machinery Economic Cost Estimates for 2005, University of Minnesota Extension Service, University of Minnesota 2005.
30. University of Illinois. Costs and fuel use for alternative tillage systems 2006. Available on the World Wide Web: http;//www.farmdoc.uiuc.edu/manage/newsletters/fefo06 07/fefo06 07.html.
31. Energy Estimator USDA. tillage 2011. http://ecat.sc.egov.usda.gov.
32. Reeder R. No-till benefits add up with diesel fuel savings 2010; http://www.thelandonline.com/currentedition/x1897235554/No-till-benefits-add-up-with-diesel-fuel-savings.
33. Calegari A, Hargrove WL, Rheinheimer DDS, Ralisch R, Tessier D, De Tourdonnet S, et al. Impact of Long-Term No-Tillage and Cropping System Management on Soil Organic Carbon in an Oxisol: A Model for Sustainability. Agronomy Journal 2002; 100:1013-9.
34. Intergovernmental Panel on Climate Change. Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories. Guidelines for National Greenhouse Gas Inventories Volume 4. Agriculture, Forestry and Other Land Use 2006; http://www.ipccnggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_02_Ch2_Generic.pdf
35. Baker JM, Ochsner TE, Venterea RT, Griffis TJ. Tillage and soil carbon sequestration—What do we really know? Agric Ecosyst Environ 2007; 118:1-5; http://dx.doi.org/10.1016/j.agee.2006.05.014.
36. Angers DA, Eriksen-Hamel NS. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci Soc Am J 2008; 72:1370-4; http://dx.doi.org/10.2136/sssaj2007.0342.
37. Blanco-Canqui H, Lal R. No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci Soc Am J 2008; 72:693-701; http://dx.doi.org/10.2136/sssaj2007.0233.

38. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science 2004; 304:1623-7; PMID:15192216; http://dx.doi.org/10.1126/science.1097396.
39. Lal R. Enhancing Crop Yields in the Developing Countries through Restoration of the Soil Organic Carbon Pool in Agricultural Lands. Land Degradation and Development 2005; 17:197-209; http://dx.doi.org/10.1002/ldr.696.
40. Lal R. Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food Security 2010; 2:169-77; http://dx.doi.org/10.1007/s12571-010-0060-9.
41. Bernacchi CJ, Hollinger SE, Meyers T. The conversion of the corn/soybean ecosystem to no-till agriculture may result in a carbon sink. Glob Change Biol 2005; 11:1867-72.
42. Brookes G, Barfoot P. Global impact of biotech crops: socio-economic effects 1996–2009. Journal of Biotechnology 2011; 12:1-49.
43. Gianessi L, Carpenter J. Agricultural biotechnology: Insect control benefits. Washington, DC: NCFAP 1999; http://www.ncfap.org/reports/biotech/insectcontrolbenefits.pdf.
44. Monsanto Brazil. Farm survey of conventional and Bt cotton growers in Brazil 2007 (unpublished 2008).
45. Galveo A. Farm survey findings of impact of insect resistant cotton in Brazil, Celeres, Brazil 2009 & 2010. www.celeres.br.
46. George Morris Centre. Economic & environmental impacts of the commercial cultivation of glyphosate tolerant soybeans in Ontario (unpublished report). Guelph, Ontario: Author 2004.
47. Canola Council of Canada. An agronomic & economic assessment of transgenic canola, Canola Council, Canada 2001; http://www.canola-council.org
48. Gusta M, et al. Changes in chemical toxicity following adoption of herbicide tolerant canola in western Canada, University of Saskatchewan 2009. College of Biotechnology. Working Paper.
49. Ismael Y, Bennett R, Morse S, Buthelezi T. Bt Cotton and pesticides. A case study of smallholder farmers in Makhathini Flats South Africa. Paper presented at the International ICABR Conference, Ravello, Italy 2002.
50. Doyle B. The performance of Ingard and Bollgard II cotton in Australia during the 2002/2003 and 2003/2004 seasons. Armidale, Australia: University of New England 2005.
51. Doyle B. The performance of roundup ready cotton 2001–2002 in the Australian cotton sector. Armidale, Australia: University of New England 2003.
52. Commonwealth Scientific and Industrial Research Organisation (CSIRO). The cotton consultants Australia 2005 Bollgard II comparison report. Collingwood, Australia 2005.
53. Fisher J, Tozer P. Evaluation of the environmental and economic impact of Roundup Ready Canola in the western Australian crop production system. Curtin University of Technology 2009. Technical report 11/2009, ISBN 9780 9807333-0-3.
54. Brookes G. The benefits of adopting GM insect resistant (Bt) maize in the EU: First results from 1998–2006. Int J Biotechnol 2008; 134.
55. Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2009 cotton crop, unpublished 2009.
56. Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2008 cotton crop, unpublished 2008.
57. Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2007 cotton crop, unpublished 2007.
58. Monsanto Comercial Mexico. Official report to Mexican Ministry of Agriculture of the 2005 cotton crop, unpublished 2005.
59. Traxler G, Godoy-Avilla S, Falck-Zepeda J, Espinoza-Arellano J. Transgenic cotton in Mexico: Economic and environmental impacts. Paper presented at the 5th International Conference on Biotechnology, Science and Modern Agriculture: A new industry at the dawn of the century, Ravello, Italy 2001.
60. Asia-Pacific Consortium on Agricultural Biotechnology (APCoAB). Bt cotton in India: a status report, ICRASTAT, New Delhi, India 2006.
61. IMRB International. Socio-economic benefits of Bollgard and product satisfaction (in India). Mumbai, India: Author 2006.
62. IMRB International. Socio-economic benefits of Bollgard and product satisfaction in India. Mumbai, India: Author 2007.