

Weed control changes and genetically modified herbicide tolerant crops in the USA 1996–2012

Graham Brookes*

PG Economics; Dorchester; Dorset, UK

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Abbreviations: EIQ, environmental impact quotient; GFK, GFK Crop and Animal Health Company; GM, genetically modified; HT, herbicide tolerant; Kg, kilogram; \$ US United States dollar; USDA NASS, United States Department of Agriculture National Agricultural Statistics Service

Crops that have been genetically modified (GM) to be tolerant to herbicides have been widely grown in the USA since 1996. The rapid and widespread adoption of this technology reflects the important economic and environmental benefits that farmers have derived from its use (equal to \$21.7 billion additional farm income and a 225 million kg reduction in herbicide active ingredient use 1996–2012). During this time, weed control practices in these crops relative to the 'conventional alternative' have evolved to reflect experience of using the technology, the challenges that have arisen and the increasing focus in recent years on developing sustainable production systems. This paper examines the evidence on the changing nature of herbicides used with these crops and in particular how farmers addressed the challenge of weed resistance. The evidence shows that use of the technology has resulted in a net reduction in both the amount of herbicide used and the associated environmental impact, as measured by the EIQ indicator when compared to what can reasonably be expected if the area planted to GM HT crops reverted to conventional production methods. It also facilitated many farmers being able to derive the economic and environmental benefits associated with switching from a plough-based to a no tillage or conservation tillage production system. In terms of herbicide use, the technology has also contributed to a change the profile of herbicides used. A broad range of, mostly selective herbicides has been replaced by one or 2 broad-spectrum herbicides (mostly glyphosate) used in conjunction with one or 2 other (complementary) herbicides. Since the mid-2000s, the average amount of herbicide applied and the associated environmental load, as measured by the EIQ indicator, have increased on both GM HT and conventional crops. A primary reason for these changes has been increasing incidence of weed species developing populations resistant to herbicides and increased awareness of the consequences of relying on a single or very limited number of herbicides for weed control. As a result, growers of GM HT crops have become much more proactive and diversified in their weed management programs in line with weed scientist recommendations and now include other herbicides (with different and complementary modes of action) in combination with glyphosate, even where instances of weed resistance to glyphosate have not been found. The willingness to proactively diversify weed management systems in the GM HT crops is also influenced by a desire to maintain effective weed control and hence continue to enjoy the benefits of no tillage and conservation tillage. Nevertheless, despite the increase in herbicide use in recent years, the use of GM HT technology continues to deliver significant economic and environmental gains to US farmers.

Introduction

Crops that have been genetically modified (GM) to be tolerant to herbicides (mostly to the herbicide glyphosate but also including tolerance to glufosinate) have been widely grown globally and in the USA since 1996. GM herbicide tolerant (HT) soybeans were first grown commercially in 1996, followed by

GM HT corn and cotton in 1997, canola in 1999 and sugar beet in 2007. Adoption of this technology has been rapid, and by 2013, the US planted area reached 62.1 million hectares (Brookes and Barfoot (2014a¹ and James (2013²)).

In terms of the share of the 5 arable crops in which GM HT technology have been commercialised, GM HT traits accounted for 88% of the total US plantings to these 5 crops in 2013 (there

© Graham Brookes

*Correspondence to: Graham Brookes; Email: graham.brookes@btinternet.com

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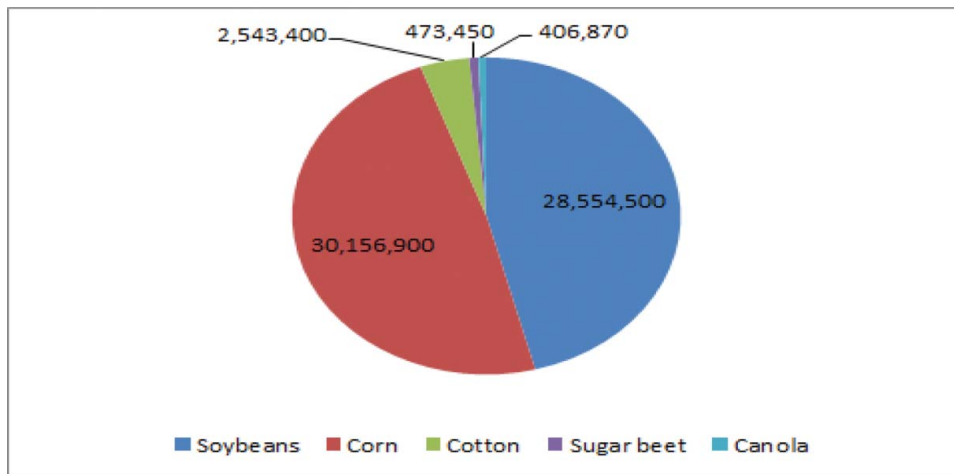


Figure 1. United States GM HT crop plantings 2013 by crop (hectares). Sources: derived from USDA, ISAAA, GfK Animal and Crop Health
 Note: Base area of the 5 crops 62.1 million ha.

were also additional GM HT crop plantings of about 700,000 ha of alfalfa). In 2013, GM HT corn accounted for the largest share (49%), followed by soybeans (46%) and cotton (4%; Fig. 1).

In relation to the share of total US plantings to each of these crops, GM HT traits accounted for 90% of soybean plantings in 2013. For the other crops, the GM HT shares in 2013 were 85% for corn, 82% for cotton, 93% for canola and 98% for sugar beet.

The rate of adoption and use of GM HT technology in US agriculture since the mid-1990s has been rapid and widespread largely because of the benefits farmers have derived from its use. In the period 1996 to 2012, the total US farm income benefit from using the technology amounted to \$21.7 billion. These gains mostly derived from reductions in the cost of production. In addition, the technology has delivered important environmental benefits through a reduction in the volume of herbicides used (225 million kg of active ingredient use 1996–2012: Brookes and Barfoot (2014b³)), a change in the profile of herbicides used (to ones which are more environmentally benign than those replaced) and through the facilitation of changes from a conventional plough-based to a no tillage or conservation tillage production system for many farmers. This change in production system has made additional positive economic contributions to farmers (and the wider economy) and delivered important environmental benefits, notably reduced levels of greenhouse gas (GHG) emissions (from reduced tractor fuel use and additional soil carbon sequestration), reduced soil erosion and increased soil water conservation (Brookes and Barfoot (2014b²)).

Against this background, this paper examines the nature of herbicide-based weed control practices (the main form of weed control) in these crops relative to the ‘conventional alternative’ since their adoption and how these practices have evolved to reflect experience of using the technology, the challenges that have arisen and the increasing focus in recent years on developing sustainable production systems. The introduction of GM HT crops occurred at a time when the emergence of weed species resistant to some

widely used herbicides was already affecting and limiting farmers’ choice of herbicides. In addition, the scope for farmers’ using no tillage and conservation tillage practices consistently was constrained by difficulties in obtaining good weed control with the existing herbicides available. As farmers increasingly adopted GM HT technology they also had to address the number of weed species resistant to the herbicides that the crops were genetically modified to be tolerant to, learn how best to minimize this occurrence and develop a sustainable, longer term weed management systems applicable to all forms of arable crop production in the USA.

Methodology

Data availability and limitations

The analysis presented is based on an extensive examination of existing farm level herbicide usage data for both GM HT and conventional crops in the USA. Assessment of the impact of the technology on herbicide use requires comparisons of the weed control measures used on GM versus the ‘conventional alternative’ form of production. This presents a number of challenges relating to both availability of data and the representativeness of the available data.

Comparison data ideally derives from farm level surveys which collect usage data on the different forms of production. A search of the literature on herbicide use change with GM HT crops shows that while there are a number of studies exploring this issue, few provide data to the herbicide (active ingredient) level. Secondly, publicly available, national level herbicide usage survey data is incomplete, and of limited value. The United States Department of Agriculture’s National Agriculture Statistical Service (USDA NASS) undertakes farm level surveys of herbicide use in field crops. However, while in the past these were conducted on an annual basis for the main field crops, for several years now, these surveys have only been conducted periodically. For example, herbicide use in soybeans was reported annually until 2006 and since then has only been surveyed in 2012; in corn, annual usage was recorded to 2003 and since then only 2005 and 2010 data have been collected. Similarly, recent herbicide usage data on the US cotton crop has only been collected in 2007 and 2010. In addition, the number of states from which data was collected varied from year to year for each crop and this lack of consistency results in an irregular data set and therefore limits the conclusions that can be drawn from the data. Furthermore, this USDA dataset is of limited value for assessing differences in herbicide usage on GM HT and conventional crops because the data is not disaggregated into use with these 2 different forms of production. The only comprehensive source of data

on herbicide use to the active ingredient level, collected on an annual basis in the US, based on farm level survey data, is from the private market research company Gfk Animal and Crop Health. This publicly available on subscription data set, widely used by many in the agricultural inputs sector, has been a primary resource used for this paper, and much of the analysis presented draws from this resource.

Nevertheless, it is important to recognize that even this dataset has limitations. To estimate the changes in amount of herbicide used with GM HT crop technology, requires an assessment of what herbicides might reasonably be expected to be used in the absence of GM HT technology on the relevant crops (in other words, if the entire crops used conventional (non GMO) production methods). The Gfk data set provides usage rates for the area planted to conventional crops, however, as the GM HT area increased, the area remaining in conventional crops became a relatively small share of the total crop area. The conventional share (not using GM HT technology) of each crop is currently very small and has remained so for a number of years. For example, the share of the total planting area accounted for by conventional crops (non GM) has been below 50% of the total since 1999 in respect of soybeans, since 2001 for cotton and canola, since 2007 for corn and 2008 for sugar beet. The conventional cropping data set is therefore unrepresentative of the levels of herbicide use that might reasonably be expected across the whole crop in the absence of GM HT technology and hence utilizing this limited data is likely to produce biased results – in other words there is self-selection bias. There are several reasons for this:

- While the degree of weed problems vary by year, region and farm, some farmers who continue to farm conventionally may have relatively low levels of weed problems, and hence see little, if any, benefit from using the GM HT traits. Their herbicide usage is typically below the levels that would reasonably be expected on an average farm with ‘average’ weed problems;
- Some of the farms that continue to use conventional seed apply production methods (including organic) which feature limited (below average) use of herbicides, increased reliance on tillage practices and increased labor inputs to manage weeds. The usage patterns of this sub-set of growers will understate usage for the majority of farmers if they all returned to farming without the use of GM HT technology;
- Some of the farmers using GM HT technology have experienced improvements in weed control from using this technology relative to the conventional control methods previously used. If these farmers were to now revert to using conventional techniques, it is likely that most would wish to maintain the levels of weed control efficacy obtained with GM HT technology and therefore may use more herbicides than they did in the pre-GM HT crop days.

Overcoming data limitations: making representative comparisons

To address the problem of bias and poor representativeness of herbicide usage data for the conventional crop system if GM HT technology was not available, the herbicide usage data were

adjusted based on input from weed scientists. Firstly, average recorded values for herbicide usage on conventional crops were used only for years when the conventional crop accounted for more than 50% of the total crop area. Secondly, in other years – when the conventional crop area fell below 50% of the total crop area (e.g., in the US from 1999 for soybeans, from 2001 for cotton and from 2007 for corn) – estimated values were used based on input from extension and industry advisors across the US of the likely usage if the whole US crop was no longer using crop biotechnology. Finally, the usage levels identified from this methodology were cross checked (and subject to adjustment) against historic average usage levels of key herbicide active ingredients from the Gfk dataset so as to minimize the scope for understating or overstating likely usage levels on the conventional alternative.

This methodology, used by others (e.g., Sankala and Blumenthal (2003⁴)) has the advantage of providing representative comparisons of current weed control practices on both GM HT crops and the conventional alternatives. Importantly, it takes into account dynamic changes in weed management practices (e.g., adapting to no-till and conservation tillage practices, controlling resistant weed species and responding with more diversified, sustainable weed management practices) and technologies (e.g., new herbicides) rather than making comparisons solely on past practices.

Assessing the environmental impact of herbicide use

The most common way that environmental impact associated with herbicide use changes with GM HT crops has been presented in the literature has been in terms of the volume (quantity) of pesticide applied. However, while the amount of pesticide applied to a crop is one way of trying to measure the environmental impact of pesticide use, this is in fact not a good measure of that parameter because the toxicity and risk of each pesticide is not directly related to the amount (weight) applied. For example, the environmental impact of applying one kg of dioxin to a crop or land is far more toxic than applying 1 kg of salt. There exist alternative (and better) measures that have been used by a number of authors of peer reviewed papers to assess the environmental impact of pesticide use change with GM crops rather than simply looking at changes in the volume of active ingredient applied to crops. In particular, there are a number of peer reviewed papers that utilize the Environmental Impact Quotient (EIQ) developed at Cornell University by Kovach et al. (1992⁵) and updated annually. This effectively integrates the various environmental impacts of individual pesticides into a single ‘field value per hectare’. The EIQ value is multiplied by the amount of pesticide active ingredient (ai) used per hectare to produce a field EIQ value. For example, the EIQ rating for glyphosate is 15.33. 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. In relative terms, products with higher field EIQ/ha values represent a potential increase in environmental concern and may require more care in how they are used.

The use of environmental indicators is now increasingly being used by researchers to assess the impact of changes in pesticide usage

and the EIQ indicator has been used by a number of researchers to examine the environmental impact of pesticide use changes with GM crops (e.g., Brimmer et al. (2004⁶), Kleiter et al. (2005⁷)). This analysis uses the EIQ indicator, a comparison of the field EIQ/ha for the conventional vs. GM HT crop production systems, which takes into account the total environmental impact or load of each system, derived from the respective field EIQ/ha values and the area planted to each type of production (GM versus conventional). The EIQ indicator provides an improved assessment of the impact of GM 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.

In the present paper, the EIQ indicator is used in conjunction with examining changes in the volume of herbicide active ingredient applied. Readers should, however, note that the EIQ is an indicator only (largely one of toxicity) and does not take into account all environmental issues and impacts. It is therefore not a comprehensive indicator.

Weed Control Practice Evolution in the US since the Introduction of GM HT Technology

GM HT (to glyphosate) soybeans

In the early years of adoption of GM HT soybeans, the primary weed control practice used was an almost total dependence on glyphosate, typically a single or 2 in-crop treatments, often in conjunction with the adoption of reduced or no tillage production system. For example, in 1998, glyphosate accounted for over 80% of total herbicide active ingredient use on GM HT soybeans. This compared with conventional soybeans, where a broader range of selective herbicides, of which chlorimuron, imazamox, imazethopir, pendamethalin and trifluralin were the most commonly used,

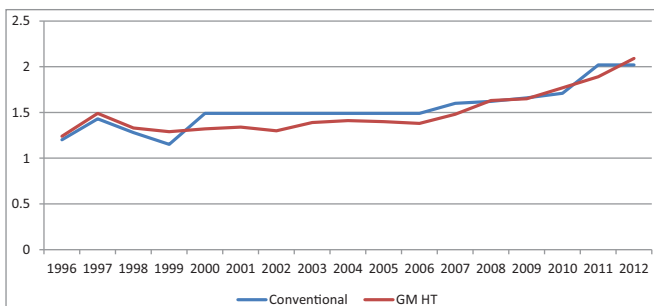


Figure 2. Herbicide active ingredient usage on GM HT and conventional soybeans in the US 1996–2012 (kg/ha). Source: derived from USDA NASS, GfK, Sankala and Blumenthal (2006⁸), Johnson and Strom (2008⁹) and representative conventional usage updated for 2009–2012 by the author Notes:

1. GM HT based on recorded usage.
2. Conventional – as recorded to 1999 when GM HT share of crop rose to over 50% of total, thereafter based on extension service/advisors assessments of representative usage levels to deliver equal levels of weed control as obtained in the GM HT crop.

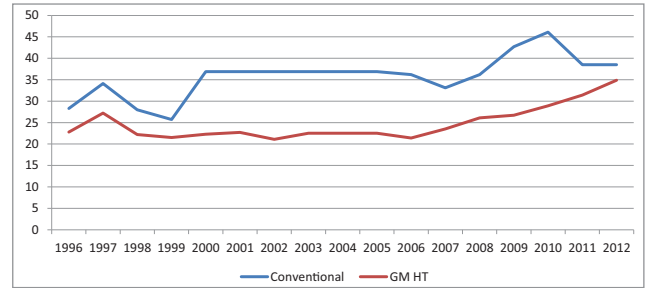


Figure 3. Herbicide usage environmental impact on GM HT and conventional soybeans in the US 1996–2012 (field eiq/ha). Source: derived from USDA NASS, GfK, Sankala and Blumenthal (2006⁸), Johnson and Strom (2008⁹) and representative conventional usage updated for 2009–2012 by the author Notes:

1. GM HT based on recorded usage.
2. Conventional – as recorded to 1999 when GM HT share of crop rose to over 50% of total, thereafter based on extension service/advisors assessments of representative usage levels to deliver equal levels of weed control as obtained in the GM HT crop.

were typically applied in several treatments. As a result, in the early years of adoption, the average amount of herbicide applied to the GM HT soybean crop tended to be higher than the amount typically applied to the conventional crop (Fig. 2), although the field EIQ/ha value for the GM HT crop was lower than the field EIQ/ha value for the conventional crop (in other words the GM HT crop provided an environmental improvement relative to the conventional alternative: Fig. 3).

Looking at the usage of herbicides on both the GM HT and conventional crop over the 1996–2012 period, the average amount of active ingredient (ai) used on GM HT soybeans has generally been similar to the average amount used on the conventional crop (Fig. 2) while the environmental load, as measured by the EIQ indicator, of GM HT soybeans has been consistently lower (and therefore better for the environment) than the conventional alternative (Fig. 3).

In terms of the average amount of herbicide used, in recent years this has increased on both the GM HT and conventional crops. In 2012, 59% of the GM HT soybean crop area received an additional herbicide treatment of one of the following active ingredients (the 4 most used herbicide active ingredients on soybeans after glyphosate (source: derived from GfK): 2,4-D (used pre crop planting), chlorimuron, flumioxazin and fomesafen (each used primarily after crop planting). This compares with 14% of the GM HT soybean crop receiving a treatment of one of these 4 herbicide active ingredients in 2006. As a result, the average amount of herbicide active ingredient applied to the GM HT soybean crop in the US (per hectare) increased by about 55% over this period. The increase in non-glyphosate herbicide use is in line with public and private sector weed scientist recommendations to diversify weed management programmes and not to rely on a single herbicide mode of action for total weed management. It is interesting to note that in 2012, glyphosate accounted for about the same share of total active ingredient use on the GM HT crop (about 80%) as in 1998, highlighting that farmers continue to realize value in using glyphosate because of

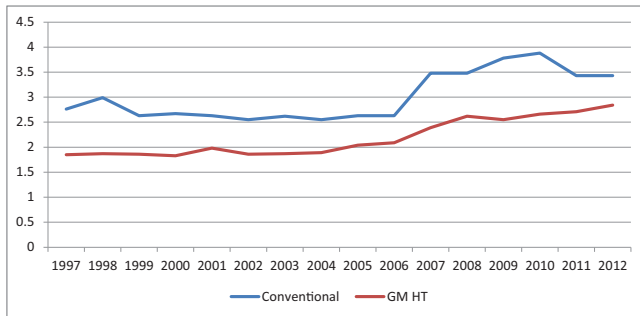


Figure 4. Herbicide active ingredient usage on GM HT and conventional corn in the US 1997–2012 (kg/ha). Source: derived from USDA NASS, GfK Kynetec, Sankala and Blumenthal (2006⁸), Johnson and Strom (2008⁹) and representative conventional usage updated for 2009–2012 by the author Notes:

1. GM HT derived from GfK Kynetec and USDA NASS.
2. Conventional – as recorded to 2007 when GM HT share of crop rose to over 50% of total, thereafter based on extension service/advisors assessments of representative usage levels to deliver equal levels of weed control as obtained in the GM HT crop.

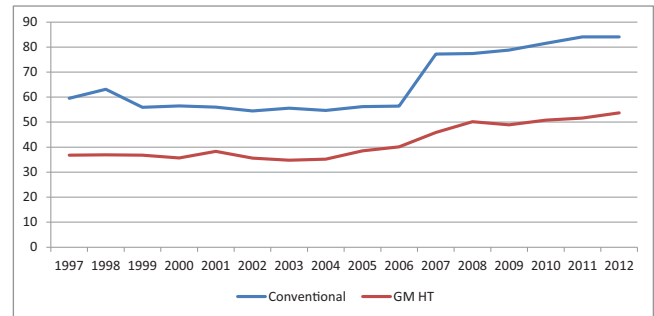


Figure 5. Herbicide usage environmental impact on GM HT and conventional corn in the US 1997–2012 (field eq/ha). Source: derived from USDA NASS, GfK, Sankala and Blumenthal (2006⁸), Johnson and Strom (2008⁹) and representative conventional usage updated for 2009–2012 by the author Notes:

1. GM HT derived from GfK and USDA NASS.
2. Conventional – as recorded to 2007 when GM HT share of crop rose to over 50% of total, thereafter based on extension service/advisors assessments of representative usage levels to deliver equal levels of weed control as obtained in the GM HT crop.

its broad spectrum activity in addition to using other herbicides. Adoption of weed scientist recommendations for herbicide use in conventional soybean crops has also resulted in an upward trend in herbicide usage. This increase in usage also reflects a more integrated approach to weed management aimed at minimising the chances of weed species developing resistance to (all) herbicides used in conventional soybean crops. It is also interesting to note that even on the small conventional crop, the average amount of herbicide active ingredient applied in the 2006–2012 period followed an upward trend in usage (by 78%).

GM HT maize

When GM HT technology was first used with the US corn crop, the main weed control practices were based on use of glyphosate, as a burn down tool where reduced/no tillage production systems were used plus an ‘in-crop’ application either before or after crop emergence. In addition, herbicides commonly used with conventional corn, notably atrazine and acetochlor, continued to be used, albeit at reduced dose rates compared to usage rates in conventional corn. As a result, the recorded average herbicide ai/ha used on the GM HT corn crop was about 0.6 to 0.7 kg/ha lower than the recorded average usage on the conventional crop in the earlier years of GM HT technology usage (Fig. 4). The environmental load, as measured by the EIQ indicator has also been consistently about 30% lower on the GM HT crop relative to the conventional crop (Fig. 5).

Over the period 1996–2012, the average herbicide active ingredient use on conventional corn has been consistently higher than usage on GM HT corn (Fig. 4). The associated environmental load, as measured by the EIQ indicator has also been worse for conventional corn when compared to GM HT corn (Fig. 5).

The average amount of herbicide active ingredient applied to both the GM HT crop and the conventional crop has increased since about 2005. These changes in herbicide usage practice on

the GM HT corn crop mirror those in the soybean crop, with farmers increasingly adopting integrated weed control practices (in which farmers use a number of herbicides rather than relying on one or 2 active ingredients) in order to reduce the risk of weed resistance developing.

Since 2006, the changes in active ingredient use on the GM HT corn crop show an increasing proportion of the GM HT crop receiving additional treatments with herbicides including acetochlor, atrazine, 2,4-D, mesotione and S metolachlor, as well as use of new chemistry such as tembutrione as recommended by public and private sector weed scientists.

GM HT cotton

In the early years of adoption, weed control in GM HT cotton crops focused on the use of glyphosate post emergence (typically 2 to 3 treatments) for all users and, for some, additional use of a pre-emergence application of herbicides such as trifluralin or pendimethalin and a lay-by treatment (e.g., of prometryn or diuron). This compared with conventional cotton, where weed suppression was based on a combination of mechanical control (e.g., between crop rows) and a broader range of selective herbicide use, of which trifluralin, pendimethalin, flumeteron, prometryn, cyanazine and MSMA were the most commonly used, typically applied in several treatments. During these early years, the recorded average herbicide ai/ha used on the GM HT cotton crop was about 2.4 to 2.5 kg/ha of herbicide active ingredient, higher than the average volume applied to the conventional crop (Fig. 6). In terms of the environmental load, as measured by the EIQ indicator the field EIQ/ha value for GM HT cotton was higher than the conventional crop partly because of the common use of mechanical weed control in conventional cotton being replaced by additional herbicide weed control in the GM HT crop (Fig. 7).

In the last 10 years, the average amount of herbicide applied to both the GM HT and conventional crop has increased. The average amount of herbicide active ingredient used on GM HT

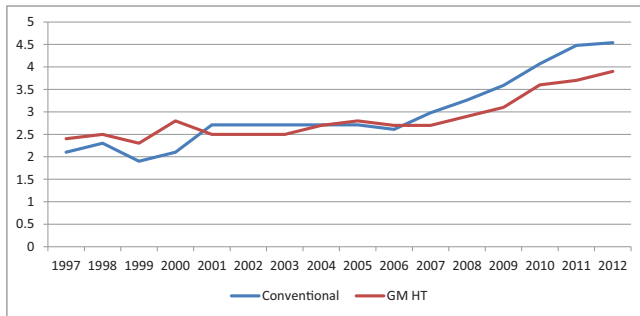


Figure 6. Herbicide active ingredient usage on GM HT and conventional cotton in the US 1997–2012 (kg/ha). Source: derived from USDA NASS, GfK, Sankala and Blumenthal (2006⁸), Johnson and Strom (2008⁹) and representative conventional usage updated for 2009–2012 by the author Notes:

1. GM HT cotton usage as recorded/derived from GfK and USDA NASS.
2. Conventional – as recorded to 2001 when GM HT share of crop rose to over 50% of total, thereafter based on extension service/advisors assessments of representative usage levels to deliver equal levels of weed control as obtained in the GM HT crop.

cotton has increased through a combination of additional usage of glyphosate (about a 30% increase in usage per hectare) in conjunction with increasing use of other herbicides. All of the GM HT crop area planted to seed tolerant to glyphosate received treatments of glyphosate and at least one of the next 5 most used herbicides (2 4-D (pre-plant) and in-crop applications of flumoxazin, fomesafen, pendimethalin and diuron) in 2012. This compares with 2006, when only 3-quarters of the glyphosate tolerant crop received at least one treatment from the next 5 most used herbicides (2 4-D, trifluralin, pyriithiobic, pendimethalin and diuron). In other words, a quarter of the glyphosate tolerant crop used only glyphosate for weed control in 2006 compared to none of the crop relying solely on glyphosate in 2012.

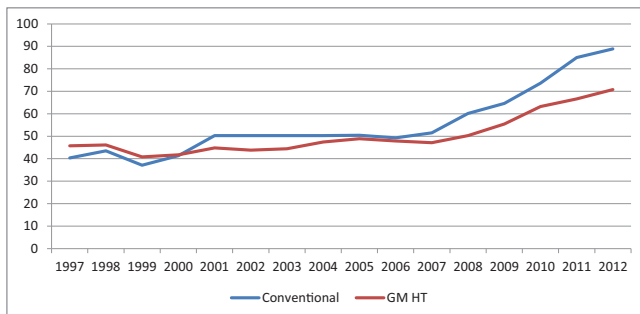


Figure 7. Herbicide usage environmental impact on GM HT and conventional cotton in the US 1997–2012 (field eq/ha). Source: derived from USDA NASS, GfK, Sankala and Blumenthal (2006⁸), Johnson and Strom (2008⁹) and representative conventional usage updated for 2009–2012 by the author Notes:

1. GM HT cotton usage as recorded/derived from GfK and USDA NASS.
2. Conventional – as recorded to 2001 when GM HT share of crop rose to over 50% of total, thereafter based on extension service/advisors assessments of representative usage levels to deliver equal levels of weed control as obtained in the GM HT crop.

As with herbicide usage on the soybean and corn crops, this increase in usage largely reflects changes in weed management practices in favor of a more integrated approach that aims to reduce and minimise the development of weed species becoming resistant to herbicides used. In addition, farmers have moved to using rates of glyphosate at the higher end of the weed scientists' recommended range as an additional means of mitigating the risk of resistance and providing better overall weed control performance.

Overall, since the widespread adoption of GM HT cotton, the average herbicide active ingredient use and the associated environmental load, as measured by the EIQ indicator, for conventional cotton is higher than GM HT cotton (Fig. 6 and Fig. 7).

GM HT (tolerant to glyphosate) sugar beet

In terms of weed control, the use of GM HT sugar beet technology has resulted in a switch in use from a number of selective herbicides to glyphosate. Before GM HT sugar beet, farmers typically used a combination of 4–6 herbicides, each at low dose rates and applied multiple times throughout the season. The GM HT treatment regime is typically 2, or possibly, 3 applications of glyphosate only.

Since the adoption of GM HT sugar beet technology, the average amount of herbicide active ingredient (per hectare) applied to the US sugar beet crop has increased by about 60% (2007–2012). Over the same period, the associated EIQ load factor (per ha) increased by about 20%. Unfortunately, there is no herbicide usage monitoring data available in the US that disaggregates usage data by type of production and therefore it is not possible to directly compare recorded usage on each of the GM HT and conventional crops. Nevertheless, based on data from industry specialists and farm surveys (e.g., Stachler J et al. (2012¹⁰)), Table 1 compares a typical conventional sugar beet herbicide treatment regime with the GM HT system in 2012. This confirms that the adoption of GM HT sugar beet has resulted in a significant increase in the average amount of herbicide applied to the US crop mainly because the weed management system in the conventional crop is based on low-use rates of the herbicides applied. In terms of the associated environmental load, as measured by the EIQ indicator, it also shows that the

Table 1. Typical herbicide regimes for GM HT vs conventional sugar beet: US 2012

	Active ingredient (kg/ha)	Field EIQ/ha value
Conventional		
Phenmedipham	0.17	2.78
Desmedipham	0.2	3.55
Ethofumesate	0.86	22.19
Clopyralid	0.18	3.26
Triflusulfuron	0.04	1.12
Clethodim	0.15	2.55
Total	1.57	35.44
GM HT sugar beet		
Glyphosate	2.39	36.64

Sources: based on GfK, Monsanto, Stachler J et al. (2012¹⁰).

Table 2. Active ingredient and field EIQ differences conventional versus GM HT canola US 1999–2012

Year	ai saving GM HT (to glyphosate: kg/ha)	ai saving GM HT (to glufosinate: kg/ha)	eiq saving GM HT (to glyphosate: field eiq/ha)	eiqsaving GM HT (to glufosinate: field eiq/ha)
1999	0.68	0.75	14.8	18.4
2000	0.68	0.75	14.8	18.4
2001	0.68	0.75	14.8	18.4
2002	0.57	0.75	17.7	18.4
2003	0.57	0.75	17.7	18.4
2004	0.79	0.83	21.2	19.8
2005	0.79	0.83	21.2	19.8
2006	0.7	0.78	19.8	18.8
2007	0.47	0.74	15.8	17.9
2008	0.47	0.74	15.8	17.9
2009	0.11	0.72	10.2	17.6
2010	0.09	0.57	9.9	14.6
2011	0.02	0.65	8.2	16.1
2012	0.06	0.57	9.4	16.6

Sources: derived from Sankala and Blumenthal (2003⁴ and 2006⁸), Johnson and Strom (2008⁹), Gfk, and updates.
Note: The USDA pesticide usage survey does not include coverage of canola.

GM HT system is slightly worse, although it is important to recognize that the conventional alternative presented here relates to a typical conventional herbicide regime used and this commonly delivers an inferior level of weed control compared to the GM HT crop.

GM HT canola

Based on analysis of typical herbicide treatments for conventional, GM glyphosate tolerant and GM glufosinate tolerant canola identified in the literature^{4,8,9} recorded in crop herbicide usage data and updates undertaken as part of this research, the changes in herbicide use and resulting environmental impact arising from adoption of GM HT canola in the US since 1999 are summarised in **Table 2** and **Table 3**. These show consistent savings in terms both of the amount of herbicide active ingredient applied and the EIQ value for both glyphosate and glufosinate tolerant canola relative to conventional canola. Since 2006, herbicide use on the GM HT canola crop has followed a similar

trend to usage on other GM HT crops in that, on the advice of both public and private sector weed scientists, farmers are focusing more attention on using a more integrated approach to weed control to reduce the chances of weed resistance developing. In canola this has involved more annual switching between glyphosate and glufosinate tolerant crops and the use of additional herbicides to glyphosate and glufosinate. The main other herbicides being used (in tank mixes), especially with glufosinate, have been quizalofop and clethodim.

Analysis

A number of information sources have been used to evaluate the changes in herbicide applications for the main crops in which GM HT technology has become widely adopted over the last 17 y. No one source provides all the answers to applicable impact questions and this presented a challenge. However, through use of data derived from different but complementary sources, some clear conclusions can be drawn.

Firstly, as indicated in the introduction, the use of GM HT technology in US agriculture, when compared to what can reasonably be expected if the area planted to GM HT crops reverted to conventional production methods, has resulted in a net reduction in both the amount of herbicide used and the associated environmental impact, as measured by the EIQ indicator. The technology also facilitated many farmers being able to derive the economic and environmental benefits associated with switching from a plough-based to a no tillage or conservation tillage production system.

In terms of herbicide use, the technology has contributed to a change the profile of herbicides used. A broad range of, mostly selective herbicides has been replaced by one or 2 broad-spectrum herbicides (mostly glyphosate and in some cases glufosinate) used in conjunction with one or 2 other (complementary) herbicides.

In the early years of adoption, GM HT technology resulted in aggregate reductions in both the volume of herbicides used

Table 3. Typical herbicide regimes for GM HT vs. conventional canola: US 2012

Active ingredient	Amount (kg/ha of crop)	Field EIQ/ha
Conventional canola		
Ethafuralin	1.0	23.3
Quizalofop	0.06	1.33
Clopyralid	0.05	0.91
Total	1.11	25.54
GM glyphosate tolerant canola		
Glyphosate	1.05	16.1
GM glufosinate tolerant canola		
Glufosinate	0.41	8.28
Quizalofop/clethodim	0.03/0.06	0.66/1.02
Total	0.44/0.47	8.94/9.3

Based on Johnson and Strom (2008⁹) and updated.

(weight of active ingredient) and the associated environmental load, as measured by the EIQ indicator, highlighting important net environmental improvements in crops such as corn and canola. In GM HT soybeans, the average amount of herbicide active ingredient applied remained largely unaltered, while the environmental load associated with the herbicides used with GM HT soybeans fell when compared to the conventional alternative. Lastly, in GM HT cotton, the average amount of herbicide active ingredient used on GM HT cotton tended to be higher than the conventional alternative, while, as in other crops, the associated environmental load associated with herbicide use on GM HT cotton was lower than the environmental load associated with the herbicides used on the conventional alternative.

Since the mid-2000s, the average amount of herbicide applied and the associated environmental load, as measured by the EIQ indicator, have increased on both GM HT and conventional crops. A primary reason for these changes has been increasing incidence of weed species developing populations resistant to herbicides and increased awareness of the consequences of relying on a single or very limited number of herbicides for weed control.

In relation to glyphosate resistant weeds, there are currently 28 weed species recognized as exhibiting populations with resistance to glyphosate worldwide, of which several are not associated with glyphosate tolerant crops. In the US, there are currently 14 weed species recognized as exhibiting resistance to glyphosate, of which at least 2 of which are not associated with glyphosate tolerant crops (see www.weedscience.org). The first weed population with resistance to glyphosate in a crop where GM HT technology had been widely adopted was identified in 2000 and since then populations of a further 13 weed species have been identified as exhibiting resistance in crops that commonly use GM HT technology. In the US, a few of the glyphosate-resistant species, such as marestail (*Conyza canadensis*), waterhemp (*Amaranthus tuberculatus*) and palmer amaranth (*Amaranthus palmeri*) are now widespread, with the affected area being possibly within a range of 10–30% (some estimates put it higher at possibly 40%) of the total area annually devoted to corn, cotton and soybeans.

The increasing onset of weed populations showing resistance to glyphosate triggered stronger recommendations to US farmers to adopt more diversified weed control practices so as to proactively manage and minimize weed resistance (Norsworthy J et al. (2012¹¹), Vencil W et al. (2012¹²)). As a result, growers of GM HT crops have become much more proactive and diversified in their weed management programmes and now include other herbicides (with different and complementary modes of action) in combination with glyphosate, even where instances of weed resistance to glyphosate have not been found. This is clearly shown in the trends in herbicide use reported earlier in this paper and summarized in Fig. 8 (examples of typical herbicide regimes used in GM HT systems are also shown in Appendix 2). The willingness to proactively diversify weed management systems in the GM HT crops is also influenced by a desire to maintain effective weed control and hence continue to enjoy the benefits of no tillage and conservation tillage.

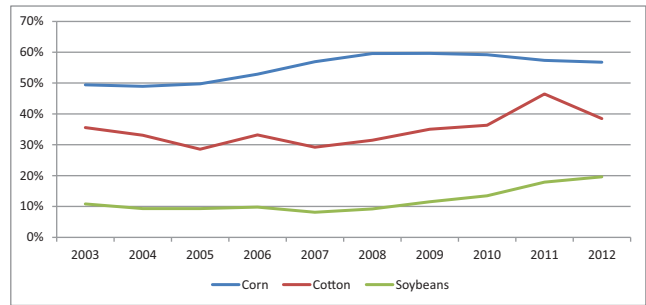


Figure 8. % of total average active ingredient used by weight with GM HT crops accounted for by non glyphosate/glufosinate herbicides 2003–2012. Source: derived from USDA NASS, Gfk.

The weed resistance development in respect of glyphosate referred to above should, nevertheless, be placed in context. Nearly all weeds have the potential to develop resistance to all herbicides: there are hundreds of resistant weed species confirmed in the International Survey of Herbicide Resistant Weeds (www.weedscience.org). Reports of herbicide resistant weeds pre-date the use of GM HT crops by decades. There are, for example, 135 weed species that are resistant to the ALS inhibitor group of herbicides and 72 weed species resistant to the photosystem II inhibitor class of herbicides. The development of weeds resistant to herbicides is therefore a problem faced by all farmers, not just those using GM HT technology. In fact, GM HT technology offered a solution to controlling some weeds that had developed resistance to mainstream herbicides used in conventional soybeans in the mid-1990s. It also offered a solution to weed resistance problems for some farmers using conventional herbicide tolerant corn crops (tolerant to ALS inhibitor herbicides). As the use of herbicides on conventional arable crops in the US is equally affected by issues of weed resistance to herbicides other than glyphosate, it is not surprising that the herbicide use patterns on conventional crops reported in this analysis have followed the same upward trends that have occurred in GM HT crops.

Overall, at the national level, in the last 6–8 y the average amount of herbicide active ingredient applied and number of herbicides used with GM HT crops has increased. In addition, during this period, the associated environmental load, as measured by the EIQ indicator, has increased. However, relative to the conventional alternative, the environmental load associated with herbicide use with GM HT crop use has continued to offer important advantages and in most cases, provides an improved environmental profile compared to the conventional alternative (as measured by the EIQ indicator). Additionally, the ability to use broad-spectrum herbicides such as glyphosate with GM HT crops has facilitated adoption and maintenance of conservation tillage systems. This fundamental change in production technique coupled with the change in profile of herbicides used with GM HT crops has resulted in, and continues to deliver, significant economic and environmental benefits to US farmers.

References

- Brookes G, Barfoot P. Economic impact of GM crops: the global income and production effects 1996–2012. *GM Crops* 2014; 5:1; 1-11 Available on open access at <http://www.landesbioscience.com>; <http://dx.doi.org/10.4161/gmcr.28278>
- James C. Global status of commercialised niotech/GM crops, ISAAA Brief No 46, International Service for the Acquisition of Agri-Biotech Applications (ISAAA). 2013; ISBN 978-1-892456-55-9. <http://www.isaaa.org>
- Brookes G, Barfoot P. Key global environmental impacts of global GM crop use 1996–2012, *GM Crops*, Forthcoming (2014b); Available on open access at <http://www.landesbioscience.com>
- 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; Available on the World Wide Web: <http://www.ncfap.org>
- 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, 139:8 pp. 1992; and annually updated. (March 2014). Available from: <http://www.nysipm.cornell.edu/publications/EIQ.html>
- Brimmer T, Gallivan G, Stephenson G. Influence of herbicide-resistant canola on the environmental impact of weed management. *Pest Manage Sci* 2005; 61:1; <http://dx.doi.org/10.1002/ps.967>
- 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
- 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; (March 2014). Available from: <http://www.ncfap.org>
- 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; (March 2014). Available from: <http://www.ncfap.org>
- Stachler J, et al. Survey of weed control and production practices on sugar beet in Minnesota and Eastern North Dakota in 2011, 2012; North Dakota State University, <http://www.sbreb.org/research/weed11/>
- Norsworthy JK, et al. Reducing the risk of herbicide resistance: best management practices and recommendations, *Weed Sci* 2012; Special Issue 31–62
- Vencil WK, et al. Herbicide resistance: towards an understanding of resistance development and the impact of herbicide resistant crops, *Weed Sci* 2012; Special Issue 2–30

Appendix 1: Typical conventional herbicide regimes required to deliver similar levels of weed control as GM HT systems 2011 and 2012

Soybeans

Conventional no tillage production systems: Mid-West

	Active ingredient (kg/ha)	Field EIQ/ha value
Option 1		
Glyphosate	1.00	15.26
2 4 D	0.66	10.05
Flumioxazin	0.07	1.78
Chlorimuron	0.02	0.4
Lactofen	0.17	6.85
Clethodim	0.11	1.83
Total	2.02	36.17
Option 2		
Glyphosate	1.00	15.26
2 4 D	0.66	10.05
Flumioxazin	0.07	1.78
Chlorimuron	0.02	0.4
Thifensulfuron	0.01	0.27
Fomesafen	0.26	6.39
Clethodim	0.11	1.83
Total	2.13	35.98
Option 3		
Glyphosate	1.00	15.26
2 4 D	0.66	10.05
Sulfentrazone	0.2	2.39
Cloransulam	0.06	0.8
Clethodim	0.11	1.83
Total	2.03	30.33

Conventional no tillage production systems: South

	Active ingredient (kg/ha)	Field EIQ/ha value
Option 1		
Glyphosate	1.00	15.26
2 4 D	0.66	10.05
Flumioxazin	0.07	1.78
Metalochlor	1.36	29.97
Fomesafen	0.30	7.32
Clethodim	0.11	1.83
Total	3.5	66.21
Option 2		
Glyphosate	1.00	15.26
2 4 D	0.66	10.05
Flumioxazin	0.07	1.78
Chlorimuron	0.02	0.4
Fomesafen	0.37	9.03
Clethodim	0.11	1.83
Total	2.23	38.35
Option 3		
Glyphosate	1.00	15.26
2 4 D	0.66	10.05
Metalochlor	1.36	29.97
Fomesafen	0.3	7.32
Aciflora	0.26	6.21
S Metalochlor	1.45	31.88
Clethodim	0.11	1.83
Total	5.14	102.52

Conventional crop and tillage production systems: South

	Active ingredient (kg/ha)	Field EIQ/ha value
Option 1		
Flumioxazin	0.07	1.78
Metalochlor	1.19	26.14
Fomesafen	0.26	6.38
Clethodim	0.11	1.83
Total	1.63	36.13
Option 2		
Flumioxazin	0.07	1.78
Chlorimuron	0.02	0.4
Fomesafen	0.26	6.39
Clethodim	0.11	1.83
Total	0.46	10.4
Option 3		
Metalochlor	1.36	29.97
Fomesafen	0.3	7.32
Acifloren	0.26	6.21
S Metalochlor	1.45	31.88
Clethodim	0.11	1.83
Total	3.48	77.21

Weighted average all by tillage types: ai/ha 2.02 kg/ha, EIQ/ha 38.47.

Corn
Conventional no tillage production systems

	Active ingredient (kg/ha)	Field EIQ/ha value
Option 1		
Glyphosate	1.1	17.01
2 4 D	0.72	11.12
Acetochlor	1.88	37.32
Atrazine	1.45	33.21
Mesotrione	0.14	2.64
Nicosulfuron	0.02	0.48
Total	5.31	101.78
Option 2		
Glyphosate	1.1	17.01
2 4 D	0.72	11.12
Acetochlor	0.94	18.66
Clopyralid	0.1	1.83
Flumetsulam	0.03	0.56
Dicamba	0.19	4.9
Diflufenzopyr	0.04	0.69
Nicosulfuron	0.02	0.48
Total	3.14	55.54
Option 3		
Glyphosate	1.1	17.01
2 4 D	0.72	11.12
S Metalochlor	1.51	33.13
Atrazine	0.73	16.61
Mesotrione	0.14	2.64
Tembotrione	0.08	3.64
Nicosulfuron	0.02	0.48
Total	4.30	84.63

Conventional crop and tillage production systems

	Active ingredient (kg/ha)	Field EIQ/ha value
Option 1		
Acetochlor	1.88	37.32
Atrazine	1.45	33.21
Tembotrione	0.08	3.64
Nicosulfuron	0.02	0.48
Total	3.43	74.65
Option 2		
Acetochlor	0.94	18.66
Clopyralid	0.1	1.83
Flumetsulam	0.03	0.56
Mesotrione	0.14	2.64
Nicosulfuron	0.02	0.48
Total	1.23	24.17
Option 3		
S Metalochlor	1.51	33.13
Atrazine	0.73	16.61
Mesotrione	0.14	2.64
Dicamba	0.19	4.9
Diflufenzopyr	0.04	0.69
Nicosulfuron	0.02	0.48
Total	2.63	58.45

Weighted average all by tillage types: ai/ha 3.43 kg/ha, EIQ/ha 84.1.

Cotton

	Active ingredient (kg/ha)	Field EIQ/ha value
South East		
Glyphosate	0.87	13.28
2 4 D	0.56	8.59
Paraquat	0.59	14.58
Fomesafen	0.29	7.07
Diuron	0.86	22.84
Pyrithiobac	0.16	3.4
Clethodim	0.13	2.15
Trifloxysulfuron	0.01	0.25
Prometryn	0.86	13.15
Trifloxysulfuron	0.01	0.24
Total	4.34	85.55
Mid South		
Glyphosate	0.87	13.28
Dicamba	0.28	7.38
Fomesafen	0.29	7.07
Paraquat	0.59	14.58
Diuron	0.86	22.84
Flumeturon	0.97	13.86
Pyrithiobac	0.16	1.4
Clethodim	0.13	2.15
Trifloxysulfuron	0.01	0.25
Prometryn	1.24	19.11
Trifloxysulfuron	0.01	0.35
Total	5.41	102.27
West Texas		
Trifluralin	0.99	18.67
Flumeturon	0.97	13.86
Pyrithiobac	0.16	3.4
Prometryn	1.24	19.11
Trifloxysulfuron	0.01	0.35
Diuron	0.86	22.84
Total	4.23	78.23

Regional weightings (based on planting area): Texas 56%, South East 25%, Mid South 19%.

Weighted average all by tillage types: ai/ha 4.48 kg/ha, EIQ/ha 85.0.

Appendix 2: Integrated weed management options: GM HT crops 2012

Soybeans GM HT no tillage production systems: Mid West	
	Active ingredient (kg/ha)
Option 1	
Glyphosate	1.00
2 4 D	0.66
Flumioxazin	0.07
Chlorimuron	0.02
Glyphosate	0.87
Lactofen (if difficult weeds resistant to glyphosate)	0.22
Total	2.62 (2.84)
Option 2	
Glyphosate	1.00
2 4 D	0.66
Flumioxazin	0.07
Chlorimuron	0.02
Thifensulfuron	0.01
Glyphosate	0.87
Fomesafen (if difficult weeds resistant to glyphosate)	0.33
Total	2.63 (2.96)
Option 3	
Glyphosate	1.00
2 4 D	0.66
Sulfentrazone	0.2
Cloransulam	0.06
Glyphosate	0.87
Cloransulam (if difficult weeds resistant to glyphosate)	0.22
Total	2.93 (3.01)

GM HT no tillage production systems: South

	Active ingredient (kg/ha)
Option 1	
Glyphosate	1.00
2 4 D	0.66
Flumioxazin	0.07
Glyphosate	0.87
Metalochlor (if difficult weeds resistant to glyphosate)	1.36
Fomesafen (if difficult weeds resistant to glyphosate)	0.30
Total	2.6 (4.26)
Option 2	
Glyphosate	1.00
2 4 D	0.66
Flumioxazin	0.07
Chlorimuron	0.02
Glyphosate	0.87
Fomesafen (if difficult weeds resistant to glyphosate)	0.37
Total	2.62 (2.99)
Option 3	
Glyphosate	1.00
2 4 D	0.66
Metalochlor	1.36
Fomesafen	0.3
Glyphosate	0.87
Aciflora (if difficult weeds resistant to glyphosate)	0.26
S Metalochlor (if difficult weeds resistant to glyphosate)	1.45
Total	4.19 (5.9)

GM HT conventional tillage production systems: South

	Active ingredient (kg/ha)
Option 1	
Flumioxazin	0.07
Glyphosate	0.87
Metalochlor	1.33
Glyphosate	0.87
Fomesafen (if difficult weeds resistant to glyphosate)	0.15
Total	3.14 (3.29)
Option 2	
Flumioxazin	0.07
Chlorimuron	0.02
Glyphosate	0.87
Fomesafen (if difficult weeds resistant to glyphosate)	0.26
Total	0.96 (1.22)
Option 3	
Metalochlor	1.36
Fomesafen	0.15
Glyphosate	0.87
Aciflora (if difficult weeds resistant to glyphosate)	0.26
S Metalochlor (if difficult weeds resistant to glyphosate)	1.45
Total	2.38 (4.09)

Corn

Conventional no tillage production systems

	Active ingredient (kg/ha)
Option 1	
Glyphosate	1.1
2 4 D	0.72
Acetochlor	1.88
Atrazine	1.45
Glyphosate	0.87
Mesotrione (if difficult weeds resistant to glyphosate)	0.14
Total	6.02 (6.16)
Option 2	
Glyphosate	1.1
2 4 D	0.72
Acetochlor	0.94
Clopyralid	0.1
Flumetsulam	0.03
Glyphosate	0.87
Dicamba (if difficult weeds resistant to glyphosate)	0.19
Diflufenzopyr (if difficult weeds resistant to glyphosate)	0.04
Total	3.76 (3.99)
Option 3	
Glyphosate	1.1
2 4 D	0.72
S Metalochlor	1.51
Atrazine	0.73
Mesotrione	0.14
Glyphosate	0.84
Tembotrione (if difficult weeds resistant to glyphosate)	0.08
Total	5.04 (5.12)

GM HT conventional tillage production systems

	Active ingredient (kg/ha)
Option 1	
Acetochlor	1.88
Atrazine	1.45
Glyphosate	0.87
Tembotrione (if difficult weeds resistant to glyphosate)	0.08
Total	4.2 (4.28)
Option 2	
Acetochlor	0.94
Clopyralid	0.1
Flumetsulam	0.03
Glyphosate	0.87
Mesotrione (if difficult weeds resistant to glyphosate)	0.14
Total	1.94 (2.08)
Option 3	
S Metalochlor	1.51
Atrazine	0.73
Mesotrione	0.14
Glyphosate	0.87
Dicamba (if difficult weeds resistant to glyphosate)	0.19
Diflufenzopyr (if difficult weeds resistant to glyphosate)	0.04
Total	3.25 (3.48)

GM HT cotton

	Active ingredient (kg/ha)
South East	
Glyphosate	0.87
2 4 D	0.56
Paraquat (if difficult weeds resistant to glyphosate)	0.59
Fomesafen	0.29
Diuron	0.86
Glyphosate	0.87
Acetochlor	1.26
Glyphosate	0.87
Acetochlor (if difficult weeds resistant to glyphosate)	1.26
Glyphosate (if difficult weeds resistant to glyphosate)	0.87
Diuron (if difficult weeds resistant to glyphosate)	1.12
Total	6.17 (9.42)
Mid South	
Glyphosate	0.87
Dicamba	0.28
Paraquat (if difficult weeds resistant to glyphosate)	0.59
Flumeturon	0.07
Glyphosate	0.87
Acetochlor	1.26
Glyphosate	0.87
Acetochlor (if difficult weeds resistant to glyphosate)	1.26
Glyphosate (if difficult weeds resistant to glyphosate)	0.87
Diuron (if difficult weeds resistant to glyphosate)	1.12
Total	4.81 (8.06)
West Texas	
Trifluralin	0.99
Glyphosate	0.87
Trifloxysulfuron	0.01
Glyphosate	0.87
Glyphosate (if difficult weeds resistant to glyphosate)	0.87
Diuron (if difficult weeds resistant to glyphosate)	0.86
Total	2.74 (4.47)