AgBioForum, 12(3&4): 346-357. ©2009 AgBioForum.

Glyphosate-Resistant Crops and Weeds: Now and in the Future

Stephen O. Duke
USDA, ARS

Stephen B. Powles
University of Western Australia

Glyphosate-resistant (GR) crops represent more than 80% of the 120 million ha of transgenic crops grown annually worldwide. GR crops have been rapidly adopted in soybean, maize, cotton, canola, and sugarbeet in large part because of the economic advantage of the technology, as well as the simple and superior weed control that glyphosate delivers. Furthermore, the GR crop/glyphosate technology is generally more environmentally benign than the weed management technologies that it replaced. In the Americas, except for Canada, adoption has meant continuous and intense selection pressure with glyphosate, resulting in evolution of GR weeds and shifts to weed species that are only partially controlled by glyphosate. This development is jeopardizing the benefits of this valuable technology. New transgenic crops with resistance to other herbicide classes—in some cases coupled with glyphosate resistance—will be introduced soon. If used wisely, these tools can be integrated into resistance management and prevention strategies. Greater diversity in weed management technologies is badly needed to preserve the utility of the GR crop/glyphosate technology.

Key words: biotech crop, glyphosate, GMO, herbicide resistance, transgenic crop, weed.

Introduction

The adoption of transgenic crops (also called GMOs and biotech crops) worldwide has been rapid and impressive, reaching 120 million ha in 2008, and continues to grow at a steady pace (James, 2008). Approximately 80% of the total area devoted to these crops has been planted with herbicide-resistant crops, virtually all being glyphosate-resistant (GR) crops. Thus, a single genetic trait—glyphosate [N-(phosphonomethyl) glycine] resistance—accounts for most of the success of transgenic crops at this time. Wide-spread adoption of GR crops and glyphosate has had significant economic effects in agriculture, from replacement of previous herbicide markets (Gianessi, 2008; Nelson & Bullock, 2003) to cost savings for farmers in weed management (Brookes & Barfoot, 2008; Gianessi, 2008). Furthermore, GR crop technology has generally reduced the adverse environmental and health impacts of weed management (e.g., Cerdeira & Duke, 2006, 2007; Gardner & Nelson, 2008).

GR crops have been a boon to farmers who have adopted them, but overuse of this single weed management technology is jeopardizing this safe, highly effective, and economical tool due to the emergence of new weed species that are only poorly controlled by glyphosate (Owen, 2008) and the evolution of GR weeds. Many factors are at play in this global scenario, including further adoption of GR crops, new GR crops being introduced, other types of herbicide-resistant crops now available or that will soon be introduced, introduction of new herbicides for use in conventional crops, and the spread of current and future GR weeds. This short review will build on earlier papers (Duke, 2005; Duke & Powles, 2008) in which we reviewed the status of GR crops, other herbicide-resistant crops, and GR weeds. Green's (2009) review focused on the technical aspects of GR crops and transgenes that will be stacked with GR transgenes.

Glyphosate-Resistant Crops

Current Status

Current Products and Adoption Rates. As of 2009, after 13 years of growing GR crops, there are five different GR crops grown in the United States (Table 1). Of these, GR cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.), canola (*Brassica napus* L. and *B. rapa* L.), and soybeans [*Glycine max* (L.) Merr.] are grown in other countries.

GR soybean adoption was rapid in the United States (Figure 1), currently representing more than 90% of the area planted to soybean. The adoption rate of GR soybean in Argentina was even more rapid, reaching almost

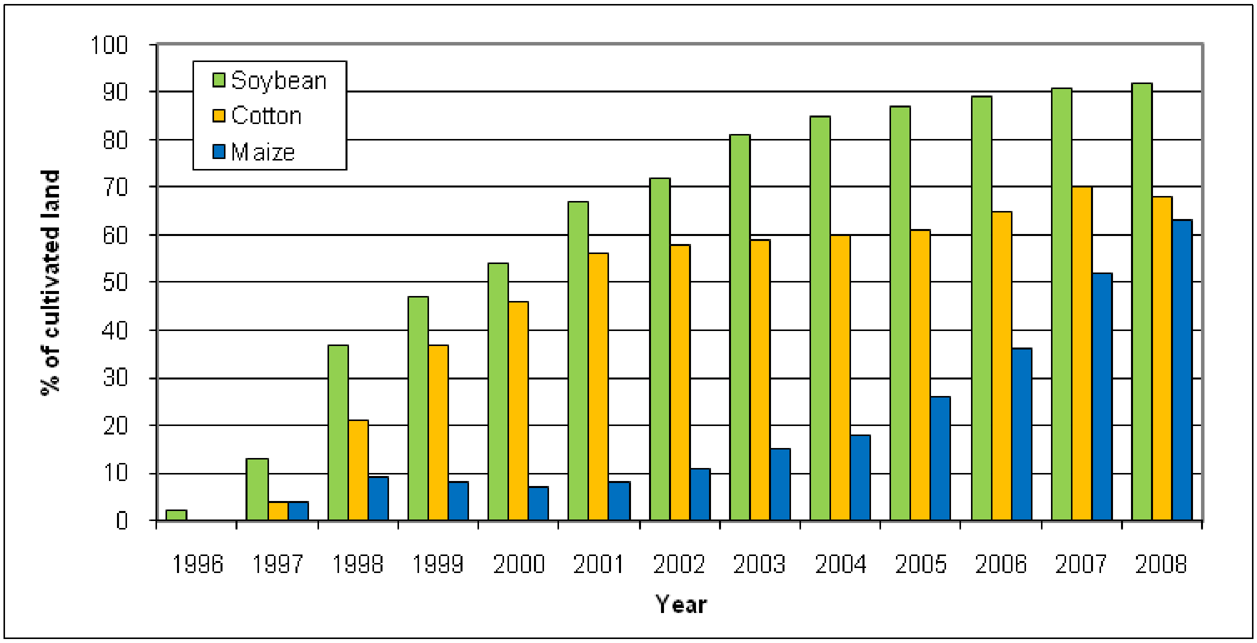

Figure 1. Adoption rate of glyphosate-resistant crops in the United States. Data from USDA ERS (2009).

90% adoption within four years of introduction (Penna & Lema, 2003). After government approvals, adoption of GR soybean has also been fast in other parts of South America, such as Brazil. Both cotton and maize have varieties that are either stand-alone GR varieties or varieties that combine GR and transgenic Bt (*Bacillus thuriengensis* toxin) traits for insect resistance. In both crops there are also stand-alone Bt varieties. To generate the data in Figure 1, adoption rates of the two types of GR varieties must be added. GR cotton adoption was initially similar to that of soybeans, but it has stabilized at about 70% (Figure 1), partly due to the use of glufosinate-resistant [2-amino-4-(hydroxymethylphosphinyl)butanoic acid] cotton in situations where it fits the weed problems better than GR cotton. Glufosinate-resistant crops are the only other transgenic, herbicide-resistant crops being grown. Although available since 1995, glufosinate-resistant crops have not been as successful as GR crops. The economics for GR maize was not quite as good as with existing weed management methods when it was first introduced, but its adoption in the United States is rising rapidly and now almost equals that of cotton (Figure 1). About 70% of the canola grown in Canada is GR (Dill, CaJacob, & Padgette, 2008), and in the United States, 62% was GR and 31% was glufosinate-resistant in 2005 (Sankula, 2006). GR sugarbeet (*Beta vulgaris* L.) was deregulated in 1999, but never planted due to concerns about acceptance by the confectionary industry. It was reintroduced in 2008 with an unprecedented rate of adoption of roughly 60% for the initial year of availability and an anticipated 95% adoption in 2009 (Thomas Schwarz, Beet Sugar Development Foundation, personal communication). The adoption rate in 2008 was limited only by the availability of transgenic seed. GR alfalfa (*Medicago sativa* L.) was introduced and well accepted by farmers in 2005, but deregulation was challenged in court by organic alfalfa growers in 2007, resulting in its reregulation and removal from the market.

Table 1. Glyphosate-resistant crops that have been deregulated in the United States (approved for sale).

Crop	Year approved
Soybean	1996
Canola	1996
Cotton	1997
Maize	1998
Sugarbeet*	1999
Alfalfa**	2005

** removed from market after first introduction, but reintroduced in 2008*

*** returned to regulated status in 2007 by court order*

The economics of herbicide-resistant crops (HRCs) for the biotechnology industry are attractive. HRCs offer a revenue stream from both a 'technology fee' added to seed costs and for purchase of the herbicide.

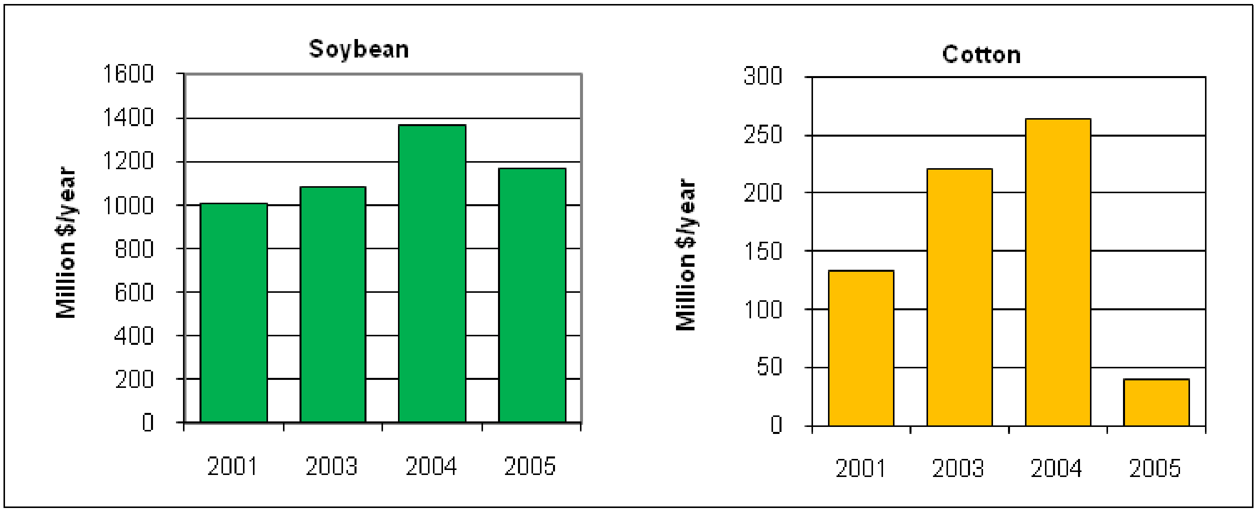

Figure 2. GR soybean and cotton increased net to grower values in the United States (adapted from Gianessi, 2008).
Data from National Center for Food and Agricultural Policy (NCFAP studies by Gianessi et al., 2002; Sankula, 2006; Sankula & Blumenthal, 2004; Sankula, Marmon, & Blumenthal, 2005).

No other type of transgenic trait offers this opportunity for dual profits from the seed and a chemical upon which the value of the gene is dependent. There has been some consideration of linking expression of transgenic traits to a chemical inducer of transgene expression (e.g., Jepson, Martinez, & Sweetman, 1998), but farmers would be unlikely to pay much for such a chemical, and the cost of applying the inducer would probably skew the economics away from such a strategy, unless the value of the trait was large.

Reasons for Adoption. Farmers have rapidly adopted GR crops/glyphosate technology for three main reasons: cost savings, better weed management, and simplicity of use. Figure 2 shows the economic benefits to US soybean and cotton growers of adopting GR crops. The reduction in the benefit to cotton growers in 2005 was due to a steep increase in the seed premium charged to farmers (Gianessi, 2008). Numerous other papers and reports document the economic gains to farmers from GR crops (e.g., Brookes & Barfoot, 2005, 2008; Serecon Management Consulting Inc. & Koch Paul Associates, 2001). Since adoption of GR crops and glyphosate, crop-infesting weeds have generally been well controlled by using glyphosate alone, thus reducing costs (no additional herbicides). After loss of patent rights in 2000, the price of glyphosate decreased substantially (by 40% in the United States [US Department of Agriculture, 2006]) as generic manufacturers worldwide began to produce and market glyphosate. Additionally, in order to compete with cheap glyphosate, the price of other herbicides that can be used with GR crops was reduced after the introduction of GR crops (Nelson & Bullock, 2003), indirectly reducing the costs of weed management to farmers using these herbicides. Furthermore, on many farms, adoption of GR crops has enabled costly soil tillage to be reduced or eliminated. However, these economic benefits of GR crops are now being threatened by the evolution of GR weeds, as discussed below.

Since glyphosate is a non-selective herbicide, virtually all weed species could be controlled in GR crops with one or two appropriately-timed post-emergent applications of glyphosate. Glyphosate is a highly systemic herbicide that is translocated to both above- and below-ground meristems, so that weed re-growth rarely occurs. Thus, when first introduced, GR crop fields generally had fewer weeds than fields in which conventional weed management was practiced. Farmers found this profound efficacy of the GR crop/glyphosate combination to be highly attractive.

Lastly, the simplicity and flexibility of the GR crop/glyphosate combination to control virtually all weed species eliminated the need for consultants to provide prescription herbicide combination solutions dependent upon crop type, herbicide selectivity, and weed spectrum, even sometimes varying with different locations within a farm. This aspect of the GR crop and glyphosate technology could be argued to favor small farms over large farms, as the expertise in devising an adequate weed management solution for a particular situation was not needed. Various surveys of farmers have found that the simplicity and flexibility of the GR crop technology has been one of the most important reasons for its adoption (e.g., Christoffoleti et al., 2008; Dill, 2005).

Environmental Impact. Both positive and negative environmental effects of GR crops are possible, but thus far the benefits appear to outweigh any negative aspects of the technology. Both *established* and *potential* environmental impacts of GR crops should be compared with the impacts of the technologies that they replace. The impacts can be associated with the transgene or with the herbicide to which the transgene is linked. Virtually all published studies and analyses of these impacts have found that the environmental benefits of substituting GR crops for conventional crops are usually substantial (e.g., Amman, 2005; Bennett, Phipps, Strange, & Grey, 2004; Brimner, Gallivan, & Stephenson, 2005; Brookes & Barfoot, 2006; Cerdeira & Duke, 2006, 2007; Devos et al., 2008; Gardner & Nelson, 2008; Kleter, Harris, Stephenson, & Unsworth, 2008; Nelson & Bullock, 2003; Shiptalo, Malone, & Owens, 2008; Wauchope et al., 2002). Of course, the potential benefits vary with the GR crop, the geographic location of use, how the farmer uses the GR crops, and the different components of environmental impact. Since nature is not static, the environmental impact will change with time as farmers using GR crop technology adjust their methods to deal with changing weeds and other problems.

The impact of GR crop/glyphosate technology on the amount of herbicides used is a changing target, as weed problems change with the technology. Glyphosate is perhaps the least toxic pesticide used in agriculture (Giesy, Dobson, & Solomon, 2000; Williams, Kroes, & Munro, 2000), with a lower acute toxicity than aspirin or many other commonly ingested compounds. Some of the "inactive" ingredients used in some formulations of glyphosate have higher levels of toxicity to some organisms than glyphosate itself. Using acute mammalian toxicity data, Gardner and Nelson (2008) compared the number of LD_{50} doses per unit area that were decreased by GR crops in the United States. Depending on the crop and the location, they calculated that conventional weed management with other herbicides could result in as much as 3,000 more LD_{50} doses per hectare with maize, more than 375 more with cotton, and more than 90 more with soybean than with GR crops.

In terms of surface and groundwater contamination, glyphosate is superior to most of the herbicides that it has replaced (reviewed by Borggaard & Gimsing, 2008; Cerdeira & Duke, 2006). Although the formulations of glyphosate for use in crops are not to be sprayed near waterways, there are formulations for use in aquatic situations. Glyphosate does not move well in soil because of its strong sorption to soil minerals, and it degrades more rapidly in most soils than most of the herbicides that it replaces (reviewed in detail by Cerdeira & Duke, 2006).

Both reduced tillage and fewer trips across the field to spray herbicides have reduced fuel utilization associated with weed management in GR crops (reviewed by Cerdeira & Duke, 2006). Bennett et al. (2004) estimated that there would be a 50% fossil-fuel savings in growing sugarbeet in Europe by switching to GR crops. Brookes and Barfoot (2006) estimated that GR crop use in 2005 reduced worldwide carbon emissions approximately equivalent to the removal of 4 million family automobiles from the road.

In many cases, the greatest damage done by conventional agriculture, other than removing land from its natural state, is caused by tillage and the potential soil erosion associated with tillage. From a practical standpoint, loss of top soil, often exacerbated by tillage, causes virtually irreversible harm to soil fertility. The primary reason for tillage has been for weed management. Glyphosate and GR crops have enabled significantly less tillage, especially in soybean and cotton (Figure 3; Dill et al., 2008; Locke, Zablotowicz, & Reddy, 2008; Penna & Lema, 2003; Powles, 2008a, 2008b). Lamentably, as GR weeds increase, use of tillage for weed management before planting is also increasing.

All of the impacts discussed to this point are associated with the benefits of glyphosate with a GR crop. Potential transgene-associated impacts are more difficult to gauge. There is concern about the potential of GR crops to create new weed problems, with GR crops themselves becoming a weed or the GR transgene escaping to relatives—either feral crops or related species—to create new weed problems. Gene flow to native populations of species with which the GR crop can cross breed could result in unwanted agricultural and/or environmental effects. The GR transgene confers no advantage where glyphosate is not sprayed, so the GR crop is no more likely to invade a natural habitat than the non-GR crop. However, GR crops are sometimes problems in agricultural fields in which glyphosate is used in subsequent years with a different GR crop (e.g., Soltani, Shropshire, & Sikkema, 2006), requiring the use of herbicides other than glyphosate to control the "volunteer" GR crop.

Gene flow to non-transgenic crops of the same species has been an economic and political problem but not

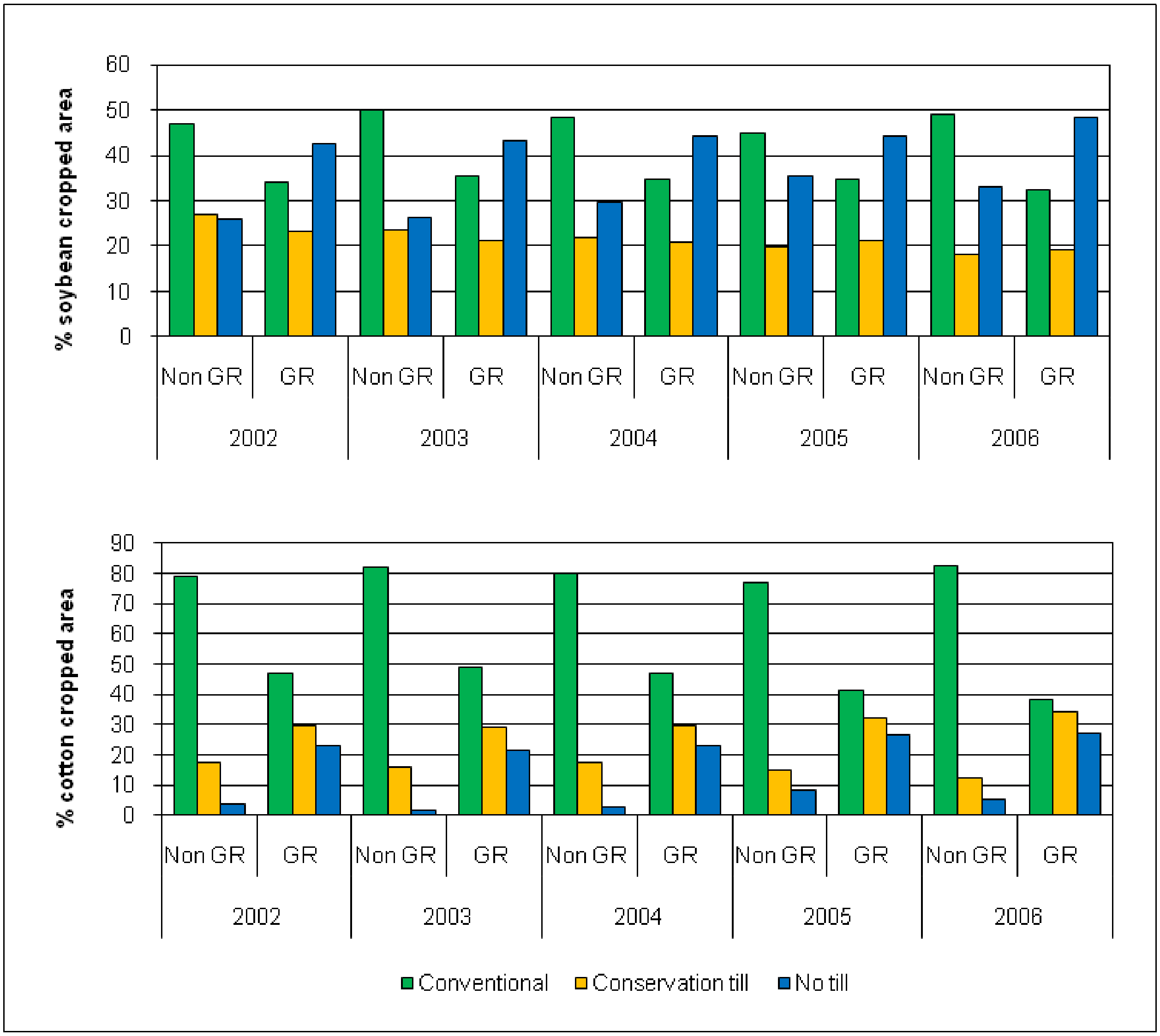

Figure 3. Comparison of US tillage practices in glyphosate-resistant (GR) and non-GR soybean (top) and cotton (bottom) from 2002 through 2006 as a percentage of hectares planted.
Used with permission from Dill et al. (2008).

an environmental threat. Organic farmers cannot retain the organic status of their crops if transgene presence is above a set limit, nor can crops be sold to markets that require the product to be non-transgenic if transgenic occurrence is above the level set by the regulatory jurisdiction. For self-pollinated crops like soybean, outcrossing is minimal, but outcrossing does occur to varying extents in maize, sugarbeet, and canola. A small degree of gene flow can occur between GR and non-GR canola (reviewed by Mallory-Smith & Zapiola, 2008). Gene flow from GR alfalfa to organic alfalfa was the ostensible reason for its re-regulation. Authorized field trials of GR bentgrass (*Agrostis stolonifera* L.) in Oregon led to extensive gene flow to naturalized or feral bentgrass (Zapiola, Campbell, Butler, & Mallory-Smith, 2008). Three years after the field trials terminated, as much as 62% of the wild bentgrass population in the vicinity possessed the GR trait, indicating that once gene flow occurs, it may be very difficult or impossible to eliminate from wild populations.

A bigger concern is the potential effect of gene flow from GR crops to weedy relatives. Even though GR transgenes offer no advantage in natural ecosystems where glyphosate is not used, when coupled with trans-

Table 2. Recent petitions for deregulation of herbicide-resistant crops (HRCs) (*http://www.aphis.usda.gov/brs/not_reg.html*) that are not yet on the market (either phenotype or new transgenes for existing phenotypes) and HRCs that have recent approval for field testing in the United States (*http://www.isb.vt.edu/cfdocs/fieldtests1.cfm*).

Crop	Herbicide(s)	Company
	Petition for deregulation	
Soybean*	Glyphosate and ALS inhibitors	Pioneer
Cotton	Glyphosate and glufosinate	Bayer Crop Science
Maize	Glyphosate and ALS inhibitors	Pioneer
Soybean	Imidazolinone	BASF
	Approval for field testing	
Alfalfa	Glyphosate and sulfonylureas	Pioneer
Soybean	Glyphosate and dicamba	Monsanto
	Glufosinate and dicamba	Monsanto
	Glyphosate	Pioneer
	Glyphosate/glufosinate/ ALS inhibitors	Pioneer
	Glyphosate and isoxazoles	M.S. Technologies
	Glufosinate	M.S. Technologies
Maize	Glyphosate	Pioneer
Bentgrass	Glufosinate	HybriGene, LLC
Cotton	Glufosinate and dicamba	Monsanto

**deregulation approved July 2008*

gene-imparting traits that would improve fitness in a natural ecosystem (e.g., insect or drought resistance), the GR trait would improve the likelihood of introgression of a gene(s) into the unintended recipient species. Once a transgene escapes to a wild species, it is unlikely that it could be eliminated from the population by human efforts, especially if it significantly enhances fitness. Transmission of GR transgenes could make weedy relatives of the GR crop much more problematic for the farmer. However, this has not happened with GR soybean, cotton, and maize, presumably because there are few or no weedy species with which they are sexually compatible in the places in which they are grown. A GR transgene has apparently introgressed from GR canola to the weed bird rape (feral *Brassica rapa* L.; Warwick, Legere, Simard, & James, 2008), but this has not yet been a problem.

There are technologies and approaches for prevention of gene flow from transgenic crops (reviewed by Cerdeira & Duke, 2006; Gealy et al., 2007; Hills, Hall, Arnison, & Good, 2007). Thus far, there does not seem to be a strong interest from the biotechnology industry to develop and employ these methods.

Products Likely to be Commercialized

New glyphosate-resistance transgenes have been discovered, and in at least one case the commercialization process for crops utilizing the new transgene is progressing (Table 2). These crops use an artificially evolved glyphosate-resistance gene (Castle et al., 2004; Siehl et al., 2005; Siehl, Castle, Gorton, & Keenan, 2007), which inactivates glyphosate by attaching an acetyl molecule to it. A gene from the soil bacterium *Bacillus licheniformis*, which encoded a weak glyphosate *N*-acetyltransferase (GAT), was selected through eleven iterations of gene shuffling to increase its activity by almost four orders of magnitude. Plants made resistant to glyphosate with this transgene are ca. 1,000-fold more resistant to glyphosate than are non-transgenic lines (Green, Hale, Pagano, Andreassi, & Gutteridge, 2009; Green, Hazel, Forney, & Pugh, 2008). A microbial transgene-encoded EPSPS with some properties that might be superior to that used in commercialized GR crops is available (Vande Berg et al., 2008). Thus, transgenes for glyphosate resistance are available for companies that do not currently have commercial GR crops.

Soybean with both the GAT gene and a gene for resistance to an acetolactate synthase-inhibiting herbicide has been deregulated and could enter the market at any time. Monsanto is developing a dicamba (2-methoxy-3, 6-dichlorobenzoic acid) resistance trait (Table 2), which detoxifies the herbicide dicamba by demethylation (Behrens et al., 2007). Dow AgroSciences has developed HRCs with resistance to auxinic herbicides like 2,4-D [(2,4-dichlorophenoxy)acetic acid] and aryloxyphenoxypropionate herbicides such as diclofop ((±)-2-[4-(2,4-dichlorophenoxy)phenoxy]propanoic acid). In combination, these herbicides would control both grass and dicot weeds, and crops resistant to these herbicides are apparently being field tested, but there is no specific information on the APHIS website as to what genes are being used. Thus, we have excluded them from Table 2. A recent abstract states that a transgene encoding α-ketoglutarate-dependent dioxygenase is used to confer resistance to these two herbicide classes (Simpson et al., 2008). A patent was filed for such a unique bacterial-derived (*Ralstonia eutropha*) transgene by Dow AgroSciences in 2005 (Wright, Lira, Merlo, & Hopkins, 2005).

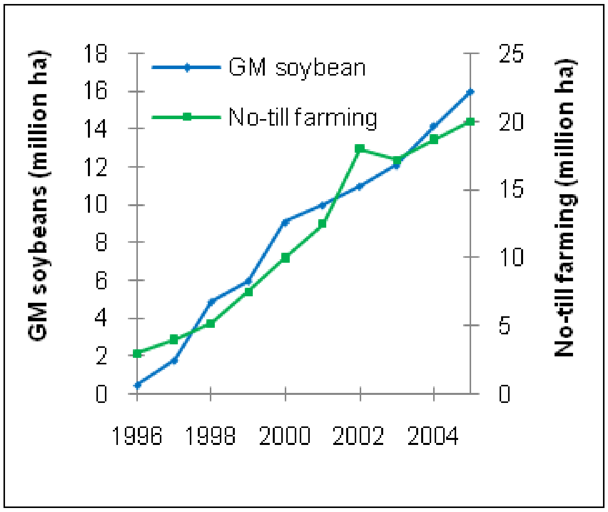

Figure 4. Adoption of GR soybean and no-till seeding in Argentina.
Data from Trigo and Cap (2006).

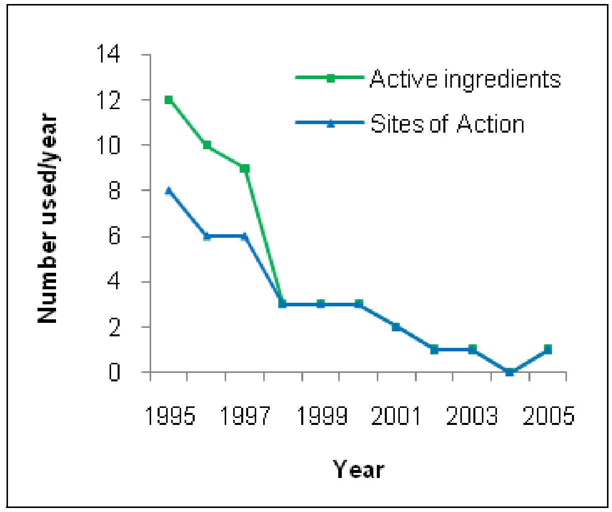

Figure 5. Number of different herbicide active ingredients and herbicide sites of action used on at least 10% of hectares from 1995 to 2005 in soybean in the United States.
Data from Dr. J. Wilcut, North Carolina State University (personal communication).

Glyphosate-Resistant Weeds

Evolution of Glyphosate-Resistant Weeds

Around the world, weed populations have been under glyphosate selection for up to 35 years (Duke & Powles, 2008). However, it is important to emphasize that until 1996, glyphosate use was restricted in agriculture to its "traditional" use for non-selective burndown of weeds prior to crop seeding or for weed control between established rows of tree, nut, and vine crops. Only with the introduction of GR crops has glyphosate become an in-crop, post-emergent, selective herbicide for use in annual, agronomic crops. Importantly, in more than 30 years of the "traditional" use of glyphosate (burndown) there has been only limited evolution of GR weeds (reviewed by Powles, 2008a, 2008b). Glyphosate continues to provide excellent weed control for most burndown uses in agriculture world-wide. Where glyphosate use is most sustainable there is diversity in weed control practices. Diversity is provided by many different factors, including alternative herbicides, mechanical tools (tillage, mowing, hand-weeding, etc.), and biological factors (grazing animals, crop competition). Clearly, where there is sufficient diversity in weed control practices, glyphosate resistance may not evolve in weed species or may do so only very slowly.

The use pattern for glyphosate changed dramatically in 1996 in those parts of the world adopting GR crops. Figure 1 shows the massive adoption of GR soybean, cotton, and maize in the United States. The adoption of GR soybean in Argentina (99%) was even more spectacular (Figure 4). It is important to emphasize that the unprecedented, widespread, and intense adoption of GR crops involves a combination of factors constituting a very strong selection intensity for the evolution of GR weeds (Powles, 2008a, 2008b) and for weed spectrum shifts to weed species only ever marginally or partially controlled with glyphosate (Owen, 2008).

GR Crops: Factors Favoring Evolution of Glyphosate-Resistant Weeds

Strong and Persistent Glyphosate Selection Pressure. The use pattern for glyphosate changed dramatically across the vast maize/soybean agro-ecosystem of the Midwestern United States after 1996 when GR crops were first grown (Figure 1). As these two crops are often in continuous rotation on the same fields, this means that glyphosate is applied to each field every year, often twice per year. As the same weed species infest soybean and maize, the weed species are under glyphosate selection every year. It is well established that herbicide resistance will evolve fastest where herbicide selection intensity is most persistent. In the Cotton Belt of Southern United States the glyphosate selection intensity is also intense because GR cotton can be grown very intensively or can be in rotation with GR soybean and/or GR maize. In Argentina, GR soybean is grown every year on the same field under no-till conditions with almost exclusive reliance on glyphosate for weed control (Figure 4).

Table 3. Glyphosate-resistant weeds infesting glyphosate-resistant crops in North and South America.

Species	Country
Amaranthus palmeri	United States
Amaranthus tuberculatus	United States
Ambrosia artemissifolia	United States
Ambrosia trifida	United States
Conyza spp	United States Brazil
Euphorbia heterophylla	Brazil
Lolium spp	United States Brazil
Sorghum halepense	Argentina United States

Data from Heap (2009).

Reduction in Herbicide Diversity. The efficacy and flexibility of glyphosate in GR crops meant that US, Argentinean, and Brazilian growers replaced previously used herbicides with glyphosate. This is starkly evident for soybean production in the United States. As GR soybeans and glyphosate were adopted, other herbicides largely disappeared from most fields (Figure 5), minimizing herbicide diversity in US soybean fields. It is well known that herbicide resistance evolution will be fastest where diversity is minimal. There can be no better example of this lack of diversity in weed control than multiple applications of glyphosate on the same field every year in GR crops (Figures 1, 4,& 5).

Adoption of No-Tillage (Reduced Weed-Control Diversity). The availability of GR crops has enabled growers in the United States, Argentina, and Brazil to adopt minimum- or no-tillage systems (Figures 3 & 4). Figure 4 shows the perfect correlation in Argentina of the adoption of GR soybeans and the adoption of no tillage. Prior to the introduction of GR soybeans, soil tillage was almost universal in Argentina (Figure 4). The environmental and agronomic benefits of no-tillage are indisputable. However, the removal of tillage removes a mechanical tool for weed control and therefore reduces weed control diversity. GR crop adoption has often meant exclusive reliance on glyphosate for weed control in no-tillage fields and thus no diversity in the form of alternative mechanical or herbicide weed control tools.

The combination of massive adoption of GR crops across vast areas and almost exclusive reliance on glyphosate for weed control every year in the same fields constitutes a potent glyphosate selection intensity. Any weed individuals possessing genetically endowed traits enabling survival under glyphosate selection will be without competition from other weeds, and will flower and produce seed that enters the soil seedbank. This is exactly what is unfolding, especially across the GR soybean, maize, and cotton agro-ecosystems in the United States, Argentina, and Brazil (Table 3). The first evolved GR weed reported in a GR crop (2001) was *Conyza canadensis* in US soybean fields (Van Gessel, 2001). In the few years since this first report, GR *Conyza* now infests at least 2 million hectares of GR crops in the United States. More worrisome are GR populations of far more economically damaging weed species (Table 3). Of special significance is the explosion in populations of GR *Amaranthus palmeri* across cotton-growing regions of the Southern US Cotton Belt. Since first reported in 2006 (Culpepper et al., 2006), thousands of US cotton fields have been infested with GR *Amaranthus palmeri*. In Georgia and North Carolina alone, in 2006 there were more than 200,000 ha of cotton fields infested with GR *Amaranthus palmeri* (Culpepper, Whitaker, MacRae, & York, 2008). This weed species is the most economically damaging weed of cotton production because it is a tall, highly competitive weed which greatly reduces cotton yield and impedes harvest. In Central US Corn-Belt states there are now many GR populations of the very vigorous, highly competitive, and economically damaging weeds *Ambrosia artemissifolia* and *Ambrosia trifida*. In Midwestern states of the United States, there are GR populations of the very competitive *Amaranthus tuberculatus*. This evolution of GR *Ambrosia* and *Amaranthus* populations is obviously a serious issue.

In parallel with the United States, GR soybean has been massively adopted in Argentina, and nearly all of this is in no-till production systems with little diversity in weed control and almost exclusive reliance on glyphosate. Additionally, in Argentina, GR maize is being adopted at a rapid rate. Therefore, the selection pressure is intense for evolution of GR weeds. So far, the very damaging weed *Sorghum halepense* (johnsongrass) has evolved glyphosate resistance across a significant area of the GR soybean crop in the Salta province (Vila-Aiub, Balbi, Gundel, Ghersa, & Powles, 2007). Brazil did not allow GR crops until well after Argentina, the United States, or Canada, and therefore GR crop adoption has only occurred over the past few years. However, rapid adoption of GR soybean, maize, and cotton is now under way. Thus far, GR populations of *Conyza* spp. and *Euphorbia heterophylla* have evolved in Brazilian GR soybean areas (Table 3). Paraguay and Uruguay are also adopting GR crops, although there are currently no reports of GR weeds in these countries. Given the dominance of GR crops in soybean, cotton, and maize agroecosystems in Argentina, Brazil, and the United States, more species than currently known (Table 3) will inevitably evolve glyphosate resistance. As glyphosate controls very many weed species, there are a large number of important weed genera and species that are at risk for evolving resistance. Particularly worrisome is that many of these genetically diverse weed species under intense glyphosate selection have already demonstrated the ability to evolve resistance to a number of other herbicide modes of action. Therefore, as they evolve glyphosate resistance, they will also retain genes endowing resistance to previously used herbicides (multiple resistance). Multiple herbicide resistance is already evident in GR *Lolium* spp. in Australia and South Africa (Neve, Sadler, & Powles, 2004; Yu, Cairns, & Powles, 2007) and GR *Amaranthus palmeri* in US cotton fields (Culpepper, York, & Marshall, 2009).

Relative to the massive GR crop adoption in the United States and Argentina, it is instructive to contrast the situation in Canada. While GR soybean and maize are grown in the Ontario province, canola is the only GR crop in the Western Grain Belt provinces (Alberta, Manitoba, Saskatchewan). In this region, the non-GR cereal crops wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) dominate, with canola as an important rotational crop. In 2006, of the 6 million ha of canola in Canada, 70% was GR, but there is also canola resistant to other herbicides (glufosinate, imidazolinones). Therefore, producers are able to diversify by alternating between GR and glufosinate- or imidazolinone-resistant canola. It is important to recognize that, on average, canola is grown on a particular cropping field in only one year in four. Clearly, the glyphosate selection intensity in this Canadian canola-cereal cropping agro-ecosystem is much less than in US, Argentinean, or Brazilian GR soybean, maize, and cotton regions. Unsurprisingly, there are currently no known cases of evolved GR weeds in Canada. This is undoubtedly due to the diversity (as it refers to glyphosate) evident in the non-GR crop cereal/GR canola Canadian cropping system, relative to that in the GR soybean/maize/cotton agroecosystems to the south. Thus, GR canola should remain sustainable in Canada if this diversity is maintained. There are important lessons that other parts of the world can learn in this sustainable use of GR crops in Canada.

Can Glyphosate Use be Sustainable?

A major lesson evident from more than three decades of glyphosate use worldwide is that, where diversity in weed management systems is maintained, weed control by glyphosate can be sustainable. Indeed, in spite of long-term use, the evolution of GR weed populations in non-GR crop burndown systems has been very limited. Thus, functionally competent gene traits endowing glyphosate resistance are relatively rare and not easily enriched in plant populations. This is why glyphosate is a remarkably robust herbicide from a resistance avoidance viewpoint. However, it is clear that, where there is very intense glyphosate selection without diversity, GR weed populations will evolve. In particular, the evolution of GR weed populations is a looming threat in areas where transgenic GR crops dominate the landscape and in which glyphosate selection is intense and without diversity. If current practices continue in these areas, GR weeds will become a major problem. This being so, the reintroduction and/or maintenance of diversity in these agroecosystems is essential if glyphosate is to be sustainable. What specifically constitutes 'diversity' will vary according to region, ecosystem, enterprises, economics, and many other factors. However, diversity will involve herbicide rotations, sequences, combinations of robust rates of different modes of action and use of non-herbicide weed-control tools. Such diversity must be introduced now in the GR crop areas of the United States, Argentina, and Brazil. Mixtures of glyphosate with effective doses of soil-residual herbicides are already being adopted, and transgenic crops with additional herbicide-resistance genes are in development (Table 2). Alternative herbicides and integration with non-herbicidal weed control tools will be required.

Regions of the world that have not yet adopted GR crops and/or intensive glyphosate usage can learn many lessons from the GR crop experience in the Americas. By not relying solely on glyphosate and maintaining some diversity in weed-management techniques, the longevity of glyphosate can be sustained for future harvests.

References

Amman, K. (2005). Effects of biotechnology on biodiversity: Herbicide-tolerant and insect-resistant GM crops. *Trends in Biotechnology*, *23*(8), 388-394.

Behrens, M.R., Mutlu, N., Chakraborty, S., Dumitru, R., Jiang, W.Z., LaVallee, B.J., et al. (2007). Dicamba resistance: Enlarging and preserving biotechnology-based weed management strategies. *Science*, *316*(5828), 1185-1188.

Bennett, R., Phipps, R., Strange, A., & Grey, P. (2004). Environmental and human health impacts of growing genetically modified herbicide-tolerant sugar beet: A life-cycle assessment. *Plant Biotechnology Journal*, *2*(4), 273-278.

Borggaard, O.K., & Gimsing, A.L. (2008). Fate of glyphosate in soil and the possibility of leaching to ground and surface waters: A review. *Pest Management Science*, *64*(4), 441-456.

Brimner, T.A., Gallivan, G.J., & Stephenson, G.R. (2005). Influence of herbicide-resistant canola on the environmental impact of weed management. *Pest Management Science*, *61*(1), 47-52.

Brookes, G., & Barfoot, P. (2005). GM crops: The global economic and environmental impact—The first nine years 1996-2004. *AgBioForum*, *8*(2-3), 187-196. Available on the World Wide Web: http://www.agbioforum.org/v8n23/v8n23a15-brookes.htm.

Brookes, G., & Barfoot, P. (2006). Global impact of biotech crops: Socio-economic and environmental effects in the first ten years of commercial use. *AgBioForum*, *9*(3), 139-151. Available on the World Wide Web: http://www.agbioforum.org/v9n3Ad/v9n3a02-brookes.htm.

Brookes, G., & Barfoot, P. (2008). Global impact of biotech crops: Socio-economic and environmental effects. *AgBioForum*, *11*(1), 21-38. Available on the World Wide Web: http://www.agbioforum.org/v11n1/v11n1a03-brookes.htm.

Castle, L.A., Siehl, D.L., Gorton, R., Patten, P.A., Chen, Y.H., Bertain, S., et al. (2004). Discovery and directed evolution of a glyphosate tolerance gene. *Science*, *304*(5674), 1151-1154.

Cerdeira, A.L., & Duke, S.O. (2006). The current status and environmental impacts of glyphosate-resistant crops: A review. *Journal of Environmental Quality*, *35*(5), 1633-1658.

Cerdeira, A.L., & Duke, S.O. (2007). Environmental impacts of transgenic herbicide-resistant crops. *CAB Rev.: Perspectives in Agriculture, Veterinary Science, Nutrition & Natural Resources*, *2*(033), 13.

Christoffoleti, P.J., Galli, A.J.B., Carvalho, S.J.P., Moreira, M.S., Nicolai, M., Foloni, L.L., et al. (2008). Glyphosate sustainability in South American cropping systems. *Pest Management Science*, *64*(4), 422-427.

Culpepper, A.S., Grey, T.L., Vencill, W.K., Kichler, J.M., Webster, T.M., Brown, S.M., et al. (2006). Glyphosate-resistant palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. *Weed Science*, *54*(4), 620-626.

Culpepper, A.S., Whitaker, J.R., MacRae, A.W., & York, A.C. (2008). Distribution of glyphosate resistant palmer amaranth (*Amaranthus palmeri*) in Georgia and North Carolina during 2005 and 2006. *The Journal of Cotton Science*, *12*(3), 306-310.

Culpepper, A.S., York, A.C., & Marshall, M.W. (2009). Glyphosate-resistant palmer amaranth in the Southeast [Abstract]. *Weed Science Society of America Abstracts*, *364.*

Devos, Y., Cougnon, M., Vergucht, S., Bulcke, R., Haesaert, G., Steurbaut, W., & Reheul, D. (2008). Environmental impact of herbicide regimes used with genetically modified herbicide-resistant maize. *Transgenic Research*, *17*(6), 1059-1077.

Dill, G.M. (2005). Glyphosate-resistant crops: History, status and future. *Pest Management Science*, *61*(3), 219-224.

Dill, G.M., CaJacob, C.A., & Padgette, S.R. (2008). Glyphosate-resistant crops: adoption, used and future considerations. *Pest Management Science*, *64*(4), 326-331.

Duke, S.O. (2005). Taking stock of herbicide-resistant crops ten years after introduction. *Pest Management Science*, *61*(3), 211-218.

Duke, S.O., & Powles, S.B. (2008). Glyphosate: A once in a century herbicide. *Pest Management Science*, *64*(4), 319-325.

Gardner, J.G., & Nelson, G.C. (2008). Herbicides, glyphosate resistance and acute mammalian toxicity: Simulating an environmental effect of glyphosate-resistant weeds in the USA. *Pest Management Science*, *64*(4), 470-478.

Gealy, D.R., Bradford, K.J., Hall, L., Hellmich, R., Raybould, A., Wolt, J., et al. (2007, December). *Implications of gene flow in the scale-up and commercial use of biotechnology-derived crops: Economic and policy consideration* (CAST Issue Paper 37). Ames, IA: Center for Agriculture Science and Technology (CAST).

Gianessi, L.P. (2008). Economic impacts of glyphosate-resistant crops. *Pest Management Science*, *64*(4), 346-352.

Gianessi, L.P., Silvers, C.S., Sankula, S., & Carpenter, J.E. (2002, June). *Plant biotechnology: Current and potential impact for improving pest management in US agriculture, an analysis of 40 case studies* (Online report). Washington, DC: National Center for Food and Agricultural Policy (NCFAP). Available on the World Wide Web: http://www.ncfap.org/40casestudies.html.

Giesy, J.P., Dobson, S., & Solomon, K.R. (2000). Ecotoxicological risk assessment for roundup herbicide. *Reviews of Environmental Contamination and Toxicology*, (167), 35-120.

Green, J.M. (2009). Evolution of glyphosate-resistant crop technology. *Weed Science*, *57*(1), 108-117.

Green, J.M., Hale, T., Pagano, M.A., Andreassi II, J.L., & Gutteridge, S.A. (2009). Response of 98140 corn with *gat4621* and *hra* transgenes to glyphosate and ALS-inhibiting herbicides. *Weed Science*, *57*(2), 142-148.

Green, J.M., Hazel, C.B., Forney, D.R., & Pugh, L.M. (2008). New multiple-herbicide crop resistance and formulation technology to augment the utility of glyphosate. *Pest Management Science*, *64*(4), 332-339.

Heap, I. (2009). *The international survey of herbicide resistant weeds* [Data file]. Corvallis, Oregon: International Survey of Herbicide Resistant Weeds. Available on the World Wide Web: http://www.weedscience.com.

Hills, M.J., Hall, L., Arnison, P.G., & Good, A.G. (2007). Genetic use restriction technologies (GURTs): Strategies to impede transgene movement. *Trends in Plant Science*, *12*(4), 177-183.

James, C. (2008). *Global status of commercialized biotech/GM crops: The first thirteen years, 1996 to 2008* (Online report). Ithaca, New York: International Service for the Acquisition of Agri-biotech Applications (ISAAA). Available on the World Wide Web: http://www.isaaa.org/resources/publications/briefs/39/executivesummary/default.html.

Jepson, I., Martinez, A., & Sweetman, J.P. (1998). Chemical-inducible gene expression systems for plants—A review. *Pesticide Science*, *54*(4), 360-367.

Kleter, G.A., Harris, C., Stephenson, G., & Unsworth, J. (2008). Comparison of herbicide regimes and the associated potential effects of glyphosate-resistant crops versus what they replace in Europe. *Pest Management Science*, *64*(4), 479-488.

Locke, M.A., Zablotowicz, R.M., & Reddy, K.N. (2008). Integrating soil conservation practices and glyphosate-resistant crops: Impacts on soil. *Pest Management Science*, *64*(4), 457-469.

Mallory-Smith, C., & Zapiola, M. (2008). Gene flow from glyphosate-resistant crops. *Pest Management Science*, *64*(4), 428-440.

Nelson, D.S., & Bullock, G.C. (2003). Simulating a relative environmental effects of glyphosate-resistant soybeans. *Ecological Economics*, *45*(2), 189-202.

Neve, P., Sadler, J., Powles, S.B. (2004). Multiple herbicide resistance in a glyphosate- resistant rigid ryegrass (*Lolium rigidum*) population. *Weed Science*, *52*(6) 920-928.

Owen, M.D.K. (2008). Weed species shifts in glyphosate-resistant crops. *Pest Management Science*, *64*(4), 377-387.

Penna, J.A., & Lema, D. (2003). Adoption of herbicide tolerant soybeans in Argentina: An economic analysis. In N. Kalaitzandonakes (Ed.), *Economic and environmental impacts of agrotechnology* (pp. 203-220). New York: Kluwer-Plenum Publishers.

Powles, S.B. (2008). Evolved glyphosate-resistant weeds around the world: Lessons to be learnt. *Pest Management Science*, *64*(4), 360-365.

Powles, S.B. (2008). Evolution in action: Glyphosate-resistant weeds threaten world crops. *Outlooks on Pest Management*, *19*(6), 256-259.

Sankula, S. (2006). *Quantification of the impacts on US agriculture of biotechnology-derived crops planted in 2005* (Final report). Washington, DC: NCFAP. Available on the World Wide Web: http://www.ncfap.org/documents/2005biotechimpacts-finalversion.pdf.

Sankula, S., & Blumenthal, E. (2004). *Impacts on US. agriculture of biotechnology-derived crops planted in 2003: An update of eleven case studies* (Online report). Washington, DC: NFCFAP. Available on the World Wide Web: http://croplife.intraspin.com/BioTech/paper.asp?id=52.

Sankula, S., Marmon, G., & Blumenthal, E. (2005). *Biotechnology-derived crops planted in 2004—Impacts on U.S. agriculture* (Online report). Washington, DC: NCFAP. Available on the World Wide Web: http://www.ncfap.org/whatwedo/pdf/2004ExecSummaryA.pdf.

Serecon Management Consulting Inc., & Koch Paul Associates (2001, January). *An agronomic and economic assessment of GMO canola*. Winnipeg, Manitoba: Canola Council of Canada. Available on the World Wide Web: http://www.canola-council.org/gmo_toc.aspx.

Shiptalo, M.J., Malone, R.W., & Owens, L.B. (2008). Impact of glyphosate-tolerant soybean and glufosinate-tolerant corn production on herbicides losses in surface runoff. *Journal of Environmental Quality*, *37*(2), 401-408.

Siehl, D.L., Castle, L.A., Gorton, R., Chen, Y.H., Bertain, S., Cho, H.J., et al. (2005). Evolution of a microbial acetyltransferase for modification of glyphosate: a novel tolerance strategy. *Pest Management Science*, *61*(3), 235-240.

Siehl, D.L., Castle, L.A., Gorton, R., & Keenan, R.J. (2007). The molecular basis of glyphosate resistance by an optimized microbial acetyltransferase. *Journal of Biological Chemistry*, *282*(15), 11446-11455.

Simpson, D.M., Wright, T.R., Chambers, R.S., Peterson, M.A., Cui, C., Robinson, A.E., et al. (2008). Dow AgroSciences herbicide tolerance traits in corn and soybean [Abstract 85]. *Proceedings of the North Central Weed Science Society*, *Champaign*, *IL*, *USA*.

Soltani, N., Shropshire, C., & Sikkema, P.H. (2006). Control of volunteer glyphosate-tolerant maize (*Zea mays*) in glyphosate-tolerant soybean (*Glycine max*). *Crop Protection*, *25*(2), 178-181.

Trigo, E.J., & Cap, E.J. (2006, December). *Ten years of GM crops in Argentine agriculture* (ArgenBio Report). Buenos Aires, Argentina: ArgenBio. Available on the World Wide Web: http://www.inta.gov.ar/ies/docs/otrosdoc/Ten_Years_GM_Crops_Argentine_Agriculture.pdf.

US Department of Agriculture, Economic Research Service (USDA ERS). (2009). *Adoption of genetically engineered crops in the US* [dataset]. Available on the World Wide Web: http://www.ers.usda.gov/Data/BiotechCrops/.

US Department of Agriculture, National Agricultural Statistics Service (USDA NASS). (2006). *Agricultural prices* [dataset]. Washington, DC: Author.

Vila-Aiub, M.M., Balbi, M.C., Gundel, P.E., Ghersa, C.M., & Powles, S.B. (2007). Evolution of glyphosate-resistant Johnson grass (*Sorghum halepense*) in glyphosate-resistant soybeans. *Weed Science*, *55*(6), 566-571.

Van Gessel, M.J. (2001). Glyphosate-resistant horseweed from Delaware. *Weed Science*, *49*(6), 703-705.

Vande Berg, B.J., Hammer, P.E., Chun, B.L., Schouten, L.C., Carr, B., Guo, R., et al. (2008). Characterization and plant expression of glyphosate-tolerant enolpyruvylshikimate phosphate synthase. *Pest Management Science*, *64*(4), 340-345.

Warwick, S.I., Legere, A., Simard, M.J., & James, T. (2008). Do escaped transgenes persist in nature? The case of an herbicide resistant transgene in a weedy *Brassica rapa* population. *Molecular Ecology*, *17*(5), 1387-1395.

Wauchope, R.D., Estes, T.L., Allen, R., Baker, J.L., Hornsby, A.G., Jones, R.L., et al. (2002). Predicted impact of transgenic, herbicide tolerant corn on drinking water quality in vulnerable watersheds of the mid-western USA. *Pest Management Science*, *58*(2), 146-160.

Williams, G.M., Kroes, R., & Munro, I.C. (2000). Safety evaluation and risk assessment of the herbicide roundup and its active ingredient, glyphosate, for humans. *Regulatory Toxicology and Pharmacology*, *31*(2), 117-165.

Wright, T.R., Lira, J.M., Merlo, D.J., & Hopkins, N. (2005). A bacterial gene for an aryloxyalkanoate dioxygenase conferring resistance to phenoxy auxin and aryloxyphenoxypropionate herbicides. World Intellectual Property Organization Patent Application WO 2005US1437 20050502.

Yu, Q., Cairns, A., Powles, S.B. (2007). Glyphosate, paraquat and ACCase multiple herbicide resistance in a *Lolium rigidum* biotype. *Planta*, *225*(2), 499-513.

Zapiola, M.L., Campbell, C., Butler, M., & Mallory-Smith, C.A. (2008). Escape and establishment of glyphosate-resistant creeping bentgrass (*Agrostis stolonifera*) in Oregon, USA: A 4-year study. *Journal of Applied Ecology*, *45*(2), 486-494.