Pest Management Science
Pest Manag Sci 64:326–331 (2008)

Glyphosate-resistant crops: adoption, use and future considerations

Gerald M Dill,* Claire A CaJacob and Stephen R Padgette
Monsanto, 700 Chesterfield Pkwy W., Chesterfield, MO 63017, USA

Abstract

BACKGROUND: Glyphosate-resistant crops (GRCs) were first introduced in the United States in soybeans in 1996. Adoption has been very rapid in soybeans and cotton since introduction and has grown significantly in maize in recent years. GRCs have grown to over 74 million hectares in five crop species in 13 countries. The intent of this paper is to update the hectares planted and the use patterns of GRC globally, and to discuss briefly future applications and uses of the technology.

RESULTS: The largest land areas of GRCs are occupied by soybean (54.2 million ha), maize (13.2 million ha), cotton (5.1 million ha), canola (2.3 million ha) and alfalfa (0.1 million ha). Currently, the USA, Argentina, Brazil and Canada have the largest plantings of GRCs. Herbicide use patterns would indicate that over 50% of glyphosate-resistant (GR) maize hectares and 70% of GR cotton hectares receive alternative mode-of-action treatments, while approximately 25% of GR soybeans receive such a treatment in the USA. Alternative herbicide use is likely driven by both agronomic need and herbicide resistance limitations in certain GR crops such as current GR cotton. Tillage practices in the USA indicate that >65% of GR maize hectares, 70% of GR cotton hectares and 50% of GR soybean hectares received some tillage in the production system. Tillage was likely used for multiple purposes ranging from seed-bed preparation to weed management.

CONCLUSION: GRCs represent one of the more rapidly adopted weed management technologies in recent history. Current use patterns would indicate that GRCs will likely continue to be a popular weed management choice that may also include the use of other herbicides to complement glyphosate. Stacking with other biotechnology traits will also give farmers the benefits and convenience of multiple pest control and quality trait technologies within a single seed.

Keywords: glyphosate; glyphosate-resistant crops; herbicide-resistant crops

1 INTRODUCTION

Glyphosate is a broad-spectrum herbicide that inhibits EPSPS (5-enolpyruvylshikimate 3-phosphate synthase). The mode of action (MOA), weed spectrum and environmental and safety profile of this herbicide have been previously reviewed.[1] The broad spectrum of weeds controlled by glyphosate and the positive environmental and safety profile of the product have made the use of glyphosate in crops for weed control an attractive consideration. However, because glyphosate was lethal to crop species, a method to develop crop safety was needed. Glyphosate-resistant crops (GRCs) were developed by inserting glyphosate-resistant clone CP4-EPSPS into plants. This transgene allows the shikimate pathway to function in the presence of glyphosate, thus allowing plants to survive glyphosate application. The rationale and development of GRCs have been previously discussed in great detail.[2–4]

Since the introduction of GR soybeans, growth of this herbicide resistance trait has been very rapid in soybean, cotton, maize and canola. The benefits of GR technology have been reviewed previously.[5,6] Economic benefits, production efficiency and flexibility, enhanced weed control and the facilitation of conservation tillage were cited as drivers for the rapid adoption of GR crops. More recent reports[7] indicate that, in 2005 alone in the United States, genetically modified (GM) crop production systems accounted for reductions in pesticide use compared with non-GM crop production systems by over 31 million kg, with 27 million kg of that reduction being attributed to herbicide resistance traits. While yield performance appeared equal to non-GR crop production systems, net income gains from GR maize, GR soybean, GR canola and GR cotton were reported to be $US 1491 million.[7] Conversely, the proliferation of GR crops has also led to concerns of weed shifts and weed resistance as the number of hectares and use of glyphosate increase. To date, biotypes of 12 species have been reported to be resistant to glyphosate worldwide,[8] and strategies to manage these biotypes as well as delay further development in other species will

* Correspondence to: Gerald M Dill, Monsanto, 700 Chesterfield Pkwy W., Chesterfield, MO 63017, USA
E-mail: gerald.m.dill.jr@monsanto.com
(Received 17 April 2007; revised version received 27 July 2007; accepted 27 July 2007)
Published online 14 December 2007; DOI: 10.1002/ps.1501

depend on growers' judicious use of multiple elements including crop rotation, alternative modes of action and varied cultural practices.[9]

Currently, crops containing biotechnology-derived traits (GM crops) are grown in 22 countries on over 100 million hectares by over 10 million farmers.[10] The author reported that 9.3 million of these farmers reside in China and India and grow GM insect-protected cotton. In addition, 29 more countries (51 in total) have granted regulatory approval for import for food and feed use in 2006. Furthermore, 68% or 69.9 million ha of the total were planted to herbicide resistance (HR) traits. The overall growth of GM crop hectares in 2006 was 13%, or 12 million ha, and GR technology was the dominant HR technology planted.[1] The intent of this paper is to update the crop statistics from 1996 through planting year 2006 and to examine use pattern data available for GR crops worldwide. The use of alternative strategies for weed management as they relate to weed shifts and weed resistance will also be discussed, as well as potential future GR crops.

2 CURRENT CROPS

2.1 Soybeans

Soybeans were the initial GR crop launched in 1996 in the USA. Adoption was very rapid (Fig. 1) and has peaked at 29 million ha of the 30.3 million ha total soybean plantings in the USA, or approximately 96%. The USA also has approximately 52% of the total GR soybeans planted globally, and, of all soybeans planted globally, GR soybeans represent approximately 64%.[1] Countries currently cultivating GR soybeans are shown in Table 1. Production cost reduction associated with weed control costs, adoption of conservation tillage practices as well as labor and time savings have been cited as reasons for this rapid adoption.[5,6] Of the global plantings of GR soybeans, 96% are grown in the USA, Argentina and Brazil. The hectares planted in these countries are shown in Fig. 2. Given the large area planted to GR soybeans in these three countries, and that this trait is established or is being established in most elite variety development programs, it is likely that GR soybeans will remain in a dominant position for the foreseeable future.

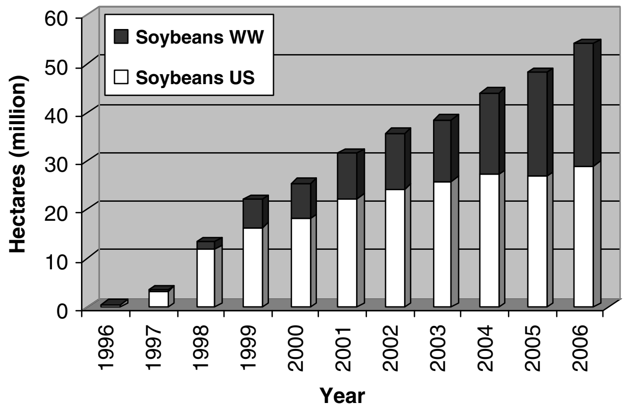

Figure 1. Worldwide GR soybean hectares planted from 1996 to 2006.

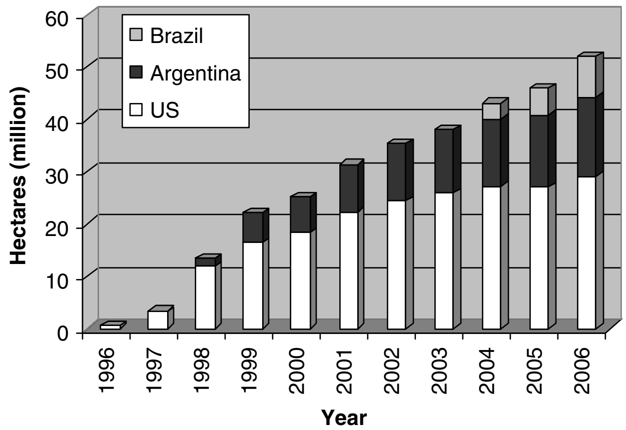

Figure 2. GR soybean plantings in the USA, Argentina and Brazil from 1996 to 2006.

Table 1. Countries where GR crops are grown as of 2006

Country	Soybean	Corn	Cotton	Canola	Alfalfa
Argentina	√	√	√		
Australia			√		
Bolivia	√				
Brazil	√				
Canada	√	√		√	
Colombia			√		
Honduras		√			
Mexico	√		√		
Paraguay	√				
Philippines		√			
South Africa	√	√	√		
United States	√	√	√	√	√
Uruguay	√				

2.2 Maize

GR maize occupies the second highest area of GR crops grown. Countries where GR maize is currently planted are shown in Table 1. The relationship between GR maize hectares planted and total GM maize hectares planted is shown in Fig. 3. Of the GM maize hectares planted globally, GR maize represents 61% of the total. Adoption rates for GR maize are shown in Fig. 4 alone and in combination with various GM insect-resistant crop technologies. GR maize adoption rates were not as rapid as those of GR soybean or GR cotton. One reason was the delay in import approvals for GR maize in the European Union (EU). Channeling GR maize grain for domestic consumption was used in the USA to gain initial market penetration. However, once approvals for import were obtained for GR maize in 2004, growth of this trait has accelerated dramatically from 2004 through 2006. An important feature of GR maize is that it is marketed in multiple stacks with transgenic insect control technologies for the European maize borer (*Ostrinia nubilalis* Hübner) as well as maize rootworm (*Diabrotica* spp.). GR maize is sold in

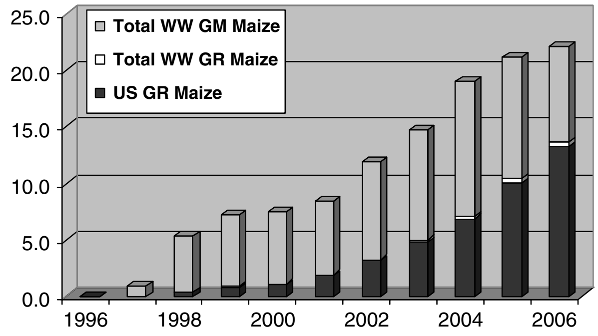

Figure 3. Worldwide biotech corn hectares, worldwide GR maize hectares and US GR maize hectares from 1996 to 2006.

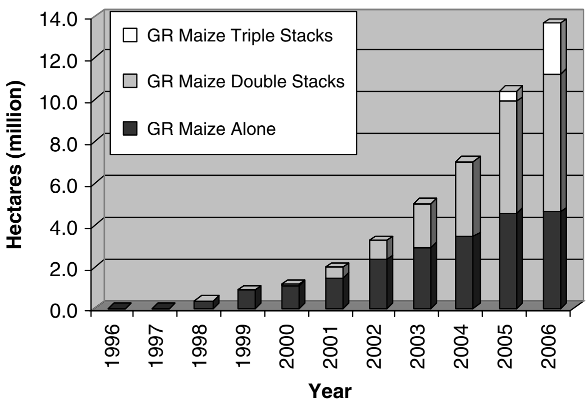

Figure 4. US maize hectares planted to GR corn alone and in combination with insect control technologies as double and triple trait stacks.

both double and triple stacks with the aforementioned technologies, which add convenience and improved control owing to the constant presence of the insect control proteins.

2.3 Cotton

Total GR cotton hectares planted from 1997 to 2006 are shown in Fig. 5, and the countries planting GR cotton in this timeframe are depicted in Table 1. GR cotton was very rapidly adopted in the USA as it represented an easier and better crop weed management system than was available at the time of launch. Inconsistencies with pre-emergent herbicide systems owing to activation rainfall requirements combined with narrow weed control spectra and lesser crop selectivity of available products drove the adoption. However, the GR cotton system was limited in that it only allowed for early season (prior to fifth leaf expansion) applications of glyphosate over the crop canopy without the potential danger of reproductive damage and subsequent yield loss. Insufficient reproductive resistance to glyphosate in the first-generation GR cotton necessitated research into a second-generation GR product, which will be covered later in this paper.

2.4 Canola

Total hectares planted by country to GR canola are shown in Fig. 6. The largest area planted to GR canola

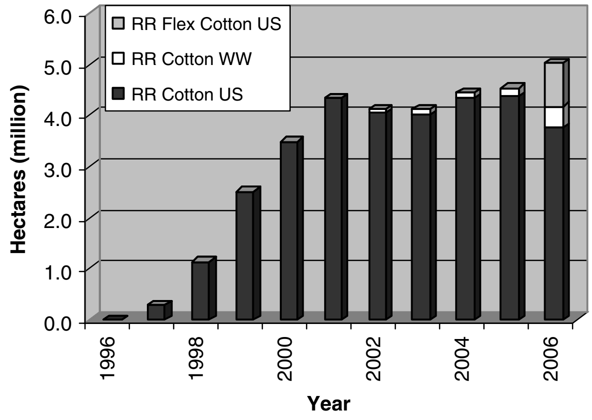

Figure 5. Worldwide GR cotton hectares from 1996 to 2006 compared with US GR cotton hectares and second-generation GR cotton (Roundup Ready Flex® cotton) launched in 2006.

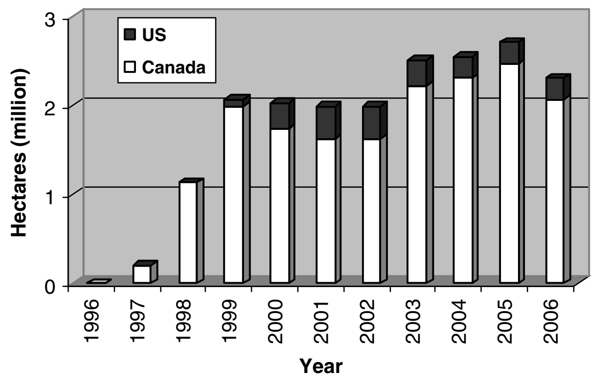

Figure 6. US and Canada GR canola hectares from 1996 through 2006.

is in Canada and represents approximately 89% of the global planting of GR canola. The current version of GR canola contains both CP4-EPSPS (glyphosate-insensitive EPSPS) as well as a glyphosate degradation gene, glyphosate oxidoreductase (GOX).[5] As with GR cotton, a second-generation GR canola is in the early stages of development.

2.5 Alfalfa

GR alfalfa was launched in 2005 in a collaboration between Monsanto and Forage Genetics International, Nampa, ID, USA. In 2006, approximately 40 000 ha of glyphosate-resistant alfalfa was planted in the USA. The technology provides growers with alternative weed control methods that improve crop safety and stand establishment and may impact on stand longevity. Obviously, patterns of use for this technology will develop as more hectares are planted and growers have the opportunity to develop weed management strategies based on GR alfalfa.

3 CURRENT USES AND PRACTICES

Weed management strategies include uses of combinations of chemical herbicides, tillage practices and GM trait usage. Growers have the option to select from

Pest Manag Sci **64**:326–331 (2008)
DOI: 10.1002/ps

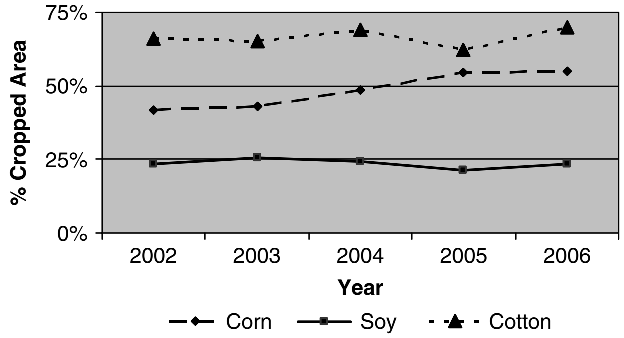

Figure 7. Percentage of US GR maize, GR soybean and GR cotton hectares receiving non-glyphosate herbicide treatments from 2002 through 2006.

an array of technologies, herbicides and land preparation options, and, in this section, data collected from market research are presented as an indication of how farmers use GR crops in comparison with non-GR counterparts.[11] The use of herbicides other than glyphosate for USA-grown GR maize, GR soybean and GR cotton for the years 2002 through 2006 is shown in Fig. 7. Both GR cotton and GR soybean are relatively consistent, with 25% of all GR soybeans receiving a non-glyphosate treatment and 65–70% of GR cotton hectares receiving a herbicide with a different MOA. GR corn does show a trend for increasing use of non-glyphosate herbicides in weed management strategies from 42% of hectares grown in 2002 to 55% of hectares grown in 2006.[11] Market research indicates that this shift largely reflects the inclusion of pre-emergence products in marketing programs that provide performance assurances to growers by providers of GRCs. It is interesting to note that market research data (data not shown) also indicate increased grower satisfaction with GR corn weed control programs that include pre-emergent herbicides in combination with or followed by glyphosate. Extending these programs to soybeans and cotton is under consideration and would likely increase the use of differing MOA herbicides that would be of help in combating weed shifts and potential weed resistance development.

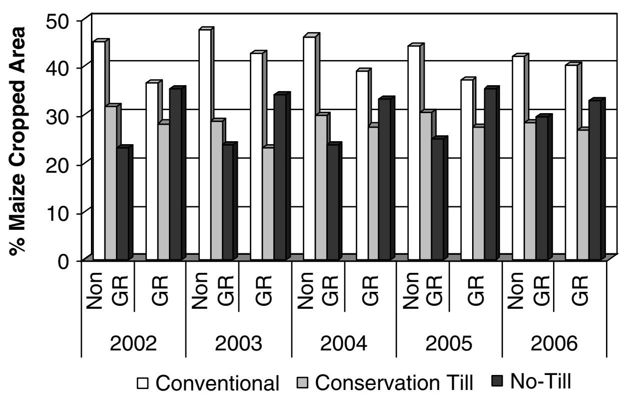

Figure 8. Comparison of US tillage practices in GR and non-GR maize from 2002 through 2006 as a percentage of hectares planted.

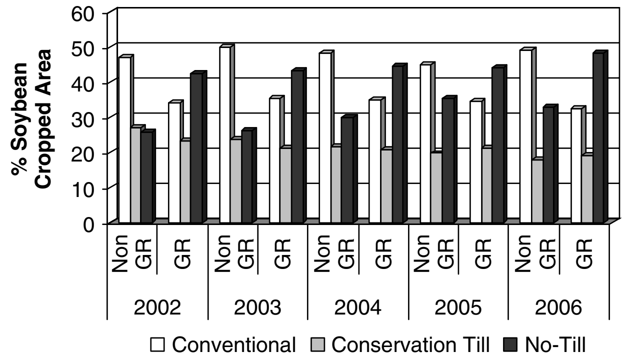

Figure 9. Comparison of US tillage practices in GR and non-GR soybean from 2002 through 2006 as a percentage of hectares planted.

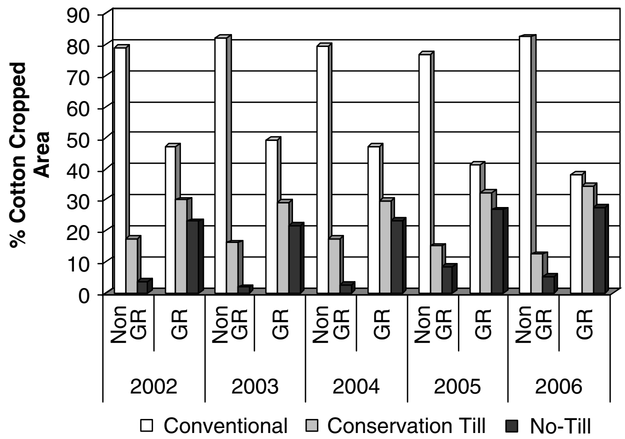

Figure 10. Comparison of US tillage practices in GR and non-GR cotton from 2002 through 2006 as a percentage of hectares planted.

Tillage is also a component of weed management, and Figs 8–10 show tillage practices for GR and non-GR maize, soybean and cotton from 2002 to 2006 as a percentage of hectares grown in the USA.[11] For the purpose of this discussion, conventional tillage refers to the use of mechanical means for seed-bed preparation and in crop weed control and post-harvest soil disturbance. Conservation tillage refers to those practices designed to leave at least 30% residue on the soil surface, and would include such practices as ridge-till and strip-till. No-till refers to direct planting into previous crop stubble without further soil disturbance. Conventional tillage was practiced to a higher degree in non-GR maize than in GR maize, although the difference appeared to diminish from 2002 to 2006 (Fig. 8). While a similar trend was observed for conservation tillage, the magnitude of the difference between GR and non-GR maize was not as large as seen in conventional tillage practices. However, the reverse trend was observed for no-till. More no-till was practiced in GR maize than in non-GR maize, although this difference did decline from 2002 to 2006. These same trends were observed in soybeans, but differences between GR and non-GR soybeans were more pronounced. Conventional tillage was practiced on 45–50% of the non-GR soybean area, while only 30–35% of the GR soybeans were raised under this practice (Fig. 9). While conservation tillage practices were similar for both soybean types, no-till was practiced to a greater degree in GR soybeans over all the years examined, although 55–60% of GR soybeans did receive some level of soil disturbance between 2002 and 2006. Figure 10 also shows much more conventional tillage practiced in non-GR cotton. Interestingly, conventional tillage still remains the dominant cultural practice in GR cotton, and in 2006 over 70% of GR cotton hectares received some tillage.[11]

These data would indicate that alternative herbicide use and tillage are still practiced to a large degree in both GR corn and GR cotton. Tillage and alternative MOA herbicide use in GR corn and GR cotton are used for various agronomic as well as weed management purposes, and these studies do not indicate the overlap of the two practices. However, the data for GR corn and GR cotton would suggest that alternative weed management is being practiced on a significant percentage of the hectares planted, and, while soybean hectares have a much higher percentage of no-till and <25% alternative MOA inclusion, the vast majority of these hectares are rotated with corn, which does introduce weed management diversity. Current trends in industry are to include the use of alternative MOA chemistries in marketing programs offered to growers in GR maize, GR soybean and GR cotton. The reason these are undertaken is twofold. Firstly, different MOAs in any weed management system are an effective tool in combating weed shifts and weed resistance. Secondly, satisfaction surveys done within Monsanto have demonstrated increased grower satisfaction with GR crops when pre-emergent products are used in combination with glyphosate in GR maize (data not shown). The programs are being expanded to other GR crops in 2006 to encourage growers to use different MOAs in their weed management strategies.

4 NEXT-GENERATION GRCS

Since the introduction of GR soybeans in 1996, the science of biotechnology has evolved significantly. Understanding transgene expression patterns, both spatial and temporal, has been key in the development of second-generation GR crops. One example is GR cotton. The original version of GR cotton was limited in its ability to withstand glyphosate applications beyond the fourth leaf stage. Applications of glyphosate beyond this point over the top of the GR cotton canopy could result in loss of fruiting structures and yield potential. Growers were forced to use glyphosate post-directed without contact with the crop or in hooded sprayers that physically shielded the crop from glyphosate. The approach to solving this issue has been described,[3] and has provided a strong constitutive chimeric promoter to express a glyphosate enzyme in sensitive tissues. In the first-generation GR cotton, developing pollen and tapetum lacked sufficient expression of CP4-EPSPS for the desired reproductive resistance to glyphosate beyond the fourth leaf. By substituting the promoter driving CP4 EPSPS expression, the next-generation GR cotton (marketed as Roundup Ready Flex® cotton) has resistance to glyphosate applications well beyond the fourth leaf stage, which can be made with no deleterious effects. This next-generation GR cotton was launched in the USA in 2006 and was planted on approximately 0.9 million ha (Fig. 5). Learning from the application of a new promoter is being applied to other crops, and second-generation GR soybean and GR canola are currently under development.[2]

5 FUTURE CROPS

Currently, GR sugarbeet is on track for commercialization in 2007 in the USA by licensees of Monsanto. GR canola received national regulatory approval in Australia but is currently awaiting the lifting of moratoria imposed on the product by a few states within Australia.

6 FUTURE TECHNOLOGIES

As with maize, GR technologies will be stacked, either through plant breeding by cross-pollinating lines containing different traits or by constructing transformation vectors containing the desired combination of traits. In this way, multiple attributes for weed and insect control as well as quality traits will be delivered in a single seed, as exemplified by GR and insect-protected cotton and maize. The same strategy will be used to combat weed management issues such as weed shifts and weed resistance. Stacking herbicide resistance traits is currently under way in both soybean and cotton in Monsanto. Providing a different MOA to be used in these crops will provide alternative weed control options to growers for combating glyphosate-resistant weeds and weeds poorly controlled by glyphosate. While providing new MOA options for farmers, this practice is not new. GR and STS (sulfonylurea soybean) have been stacked in soybean and sold commercially for several years. STS is not a biotechnology-derived trait but one developed through traditional breeding.[12] This stack is used widely and effectively in areas where soybeans are double cropped with wheat, and sulfonylurea herbicides are used in wheat production to avoid injury from herbicide carryover.

Stacked herbicide resistance traits, in combination with aggressive use of incentives to growers to utilize an array of different MOAs and cultural practices, should be effective additions to the weed management tools used. Currently, dicamba-resistant soybean and cotton are under development, and stacks with GR are planned. It is possible that, in the future, stacks with other HR traits will be made available to expand the weed management options available in major crops.

Pest Manag Sci **64**:326–331 (2008)
DOI: 10.1002/ps

In conclusion, GM crops were planted on over 100 million hectares in 2006.[10] Adoption rates of GR crops vary by crop, but continued widespread use in major grain crops will likely continue as long as growers continue to realize the economic and agronomic benefits previously cited for this technology.[5,6] Planting GR crops that also contain other HR technologies, along with the use of other agronomic practices such as alternating MOA, crop rotation and tillage, will help to sustain the benefits of GR crops. GM insect protection, GM grain oil and protein modifications and GM enhancements to generate healthier grains are all potential future GM trait combinations that will be stacked with GR in crops and made available to growers.

REFERENCES

1 Franz JE, Mao MK and Sikorski JA, *Glyphosate: a Unique Global Herbicide*, *ACS Monograph* No. 189. American Chemical Society, Washington, DC, pp. 617–642 (1997).

2 CaJacob CA, Feng PC, Reiser SE and Padgette SR, Genetically modified herbicide resistant crops, in *Modern Crop Protection Compounds*, ed. by Krämer W and Schirmer U. Wiley-VCH, Weinheim, Germany, pp. 283–316 (2007).

3 CaJacob CA, Feng PC, Heck GR, Murtaza FA, Sammons RD and Padgette SR, Engineering resistance to herbicides, in *Handbook of Biotechnology*, ed. by Christou P and Klee H. John Wiley & Sons Ltd, Chichester, UK, pp. 353–372 (2004).

4 Gressel J, *Molecular Biology of Weed Control*. Taylor and Francis, London and New York, pp. 77–219 (2002).

5 Dill GM, Glyphosate resistant crops: history, status and future. *Pest Manag Sci* **61**:219–224 (2005).

6 Gianessi L, Economic and herbicide use impacts of glyphosate-resistant crops. *Pest Manag Sci* **61**:241–245 (2005).

7 Sujatha S, *Quantification of the Impacts on US Agriculture of Biotechnology-Derived Crops Planted in 2005*. [Online]. Available: www.ncfap.org [3 December 2007].

8 Heap I, *International Survey of Herbicide Resistant Weeds.* [Online]. Available: www.weedscience.org/in.asp [3 December 2007].

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

10 James C, Global status of commercialized biotech/GM crops: 2006. *ISAA Briefs* **35**:ISAA, Ithica, NY (2006).

11 *dmrkynetec Crop Protection Studies – AgroTrak®, St Louis, MO Inc.* [Online]. Available: www.dmrkynetec.com/Index/ [3 December 2007].

12 *More Information on Herbicides, Herbicide Resistant Crops and DuPont Product Development.* [Online]. DuPont Biotechnology. Available: http://www2.dupont.com/Biotechnology/en_US/science_knowledge/herbicide_resistance/moreinfo3.html [3 December 2007].