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REVIEW

Glyphosate-resistant soybean as a weed management tool: Opportunities and challenges

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Transgenic soybean, resistant to glyphosate, represents a revolutionary breakthrough in weed control technology. Transgenic soybean is the most dominant among all transgenic crops grown commercially in the world. In 2000, glyphosate-resistant (GR) soybean was planted to 25.8 million hectares globally, which amounts to 58% of the total global transgenic crop area. The United States soybean area planted with GR soybean has increased from 2% in 1996 to 68% in 2001. Glyphosate-resistant soybean as a weed management tool has provided farmers with the opportunity and flexibility to manage a broad spectrum of weeds. The use of glyphosate in GR soybean offers another alternative to manage weeds that are resistant to other herbicides. The rapid increase in GR soybean area is caused by the simplicity of using only one herbicide and a lower cost for weed control. Adoption of GR soybean has resulted in a dramatic decrease in the area treated with other herbicides. Glyphosphate-resistant soybean should not be relied on solely to the exclusion of other weed control methods, and should be used within integrated weed management systems. Over-reliance on GR soybean could lead to problems such as shifts in weed species and population, and the development of glyphosate-resistant weeds. The challenge is for soybean farmers to understand these problems, and for weed scientists to communicate with farmers that continuous use of glyphosate may diminish the opportunity of GR soybean as a weed management tool in the future.

Keywords: glyphosate, glyphosate-resistant crops, herbicide-resistant crops, soybean, transgenic crops, weed management.

INTRODUCTION

Weeds have been with us since the dawn of civilization and are not likely to disappear, despite the use of best weed management tactics. Weeds continually interfere with profitable production of food, feed, and fiber. The development of safe, effective, and relatively inexpensive herbicides, coupled with advances in application technology during the past 50 years, have provided many successful weed management options in crop production. Herbicides provide cost-effective, timely weed control, and have helped producers become highly productive and economically viable. Soybean [*Glycine max* (L.) Merr.] is the second largest crop in the USA after corn (*Zea mays* L.). The USA leads the world in soybean plantation acreage. In 2000, approximately 97% of 30.2 million hectares of the United States soybean area was treated with herbicides to control weeds (USDA 2001).

Herbicides that control a broad spectrum of weed species often have limited use because they also injure crops (e.g. glufosinate, glyphosate). The most desirable herbicides for weed control and crop safety often have other less desirable environmental characteristics (e.g. non-target toxicity, environmental persistence). Furthermore, engineering crops for resistance to existing non-selective herbicides may be a more economically viable option for agrochemical industries than the huge costs associated with the discovery, development, and commercialization of new herbicides. Traditionally,

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herbicides have been largely tailored for use with crops rather than the crops being bred to tolerate the herbicide (Duke 1996). During the past decade, advances in biotechnology, coupled with plant breeding, have led to the development of herbicide-resistant crops. In genetically engineered soybean, via stable integration of a foreign gene with the use of molecular biology techniques and plant transformation, resistance to glyphosate was developed and commercialized (Dekker & Duke 1995; Padgette *et al.* 1995, 1996; WSSA 1998; Duke 1999). Information on glyphosate, trends in adoption of glyphosate-resistant (GR) soybean, and the impact of GR soybean on weed management during the past 5 years is briefly summarized in this review. Consumer reactions to genetically modified crops and food in Europe, Japan, and elsewhere will not be covered as the main objective of this review is to summarize the benefits and risks of GR soybean as a weed management tool.

GLYPHOSATE

Glyphosate is a non-selective, broad-spectrum herbicide used extensively throughout the world during the past three decades in preplant, post-directed, spot, and pre- and post-harvest applications (Franz *et al.* 1997; WSSA 1994). Glyphosate (acid equivalent refers to parent acid, glyphosate) at 0.21–4.2 kg ae ha^{-1} applied to foliage controls a broad-spectrum of annual, perennial, and biennial herbaceous species of grasses, sedges, and broadleaf weeds, as well as woody brush and trees. Because glyphosate is a non-selective herbicide, it causes injury when applied directly to the foliage of crops.

Glyphosate inhibits the biosynthesis of aromatic amino acids (phenylalanine, tyrosine, and tryptophan), which leads to the arrest of protein production and prevention of secondary product formation (Grossbard & Atkinson 1985; Franz *et al.* 1997). Glyphosate inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase in the shikimic acid pathway (Amrhein *et al.* 1980). Enzyme 5-enolpyruvylshikimate-3-phosphate synthase catalyzes the reaction of shikimate-3-phosphate and phosphoenolpyruvate to form 5-enolpyruvylshikimate-3-phosphate and phosphate. Glyphosate is the only herbicide reported to inhibit EPSP synthase (Bradshaw *et al.* 1997). The enzyme 5-enolpyruvylshikimate-3-phosphate synthase is present in all plants, bacteria, and fungi, but not in animals (Padgette *et al.* 1995). Glyphosate is toxicologically and environmentally benign (low toxicity to non-target organisms, low or no groundwater movement, and limited persistence). Thus, glyphosate is considered an environmentally safe herbicide.

TRENDS IN THE ADOPTION OF GLYPHOSATE-RESISTANT SOYBEAN

Several crops that possess genes rendering them resistant to glyphosate have recently been marketed (WSSA 1998; Duke 1999; Thayer 2000). Glyphosate-resistant canola (*Brassica napus* L.), corn, cotton (*Gossypium hirsutum* L.), and soybean have been commercialized since the mid-1990s. Transgenic crops resistant to other herbicides such as bromoxynil (cotton) and glufosinate (canola and corn) were commercialized in the mid-1990s.

In 2000, just four countries grew 99% of the 44.2 million hectares of global transgenic crop area (James 2000). Most of the transgenic crops are grown in the USA. In 2000, the USA had approximately 68% of the global transgenic crop area, followed by Argentina (23%), Canada (7%), and China (1%). The remaining 1% was grown in nine other countries (James 2000). Transgenic soybean was the most dominant among all transgenic crops grown commercially in the world. In 2000, transgenic soybean was planted to 25.8 million hectares globally or to 58% of the total global transgenic crop area. As of 2000, only GR soybean has been commercialized and represents all transgenic soybean area.

In the USA, GR soybean varieties were commercialized for planting in 1996. Glyphosate-resistant soybean, commercially known as 'Roundup Ready' soybean, remains unaffected when treated with the herbicide because of the expression of a glyphosate-resistant EPSP synthase with a high catalytic activity in the presence of glyphosate. The continued action of the glyphosate-resistant EPSP synthase enzyme helps to maintain aromatic amino acid levels in plants. Glyphosate-resistant soybean provides producers with the flexibility to control a broad spectrum of weeds in the crop with minimal concern for crop damage. Glyphosate-resistant soybean has been widely adopted by American farmers since its introduction in 1996 (Fig. 1). The United States soybean area planted with GR soybean has increased from 2% in 1996 to 68% in 2001 (USDA 2001; Carpenter & Gianessi 2001). The rapid increase in GR soybean area is because of several factors: the ability to control most grass and broadleaf weeds; the simplicity of using only one herbicide; and the lower cost of weed control.

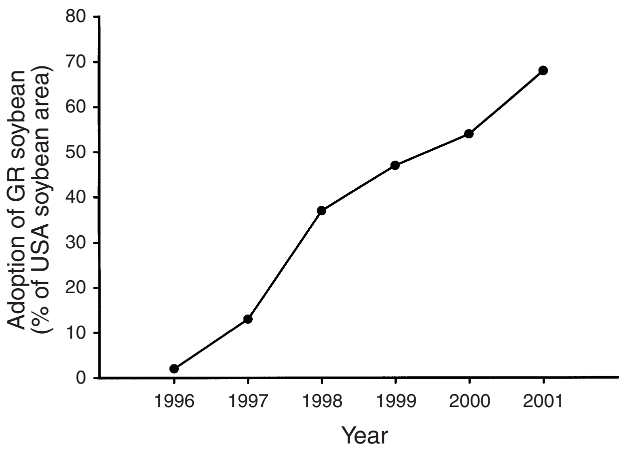

Fig. 1. Adoption of glyphosate-resistant soybean in the USA since its introduction in 1996 (USDA 2001; Carpenter & Gianessi 2001).

Table 1. Maximum allowable application rates of glyphosate in glyphosate-resistant soybean (Anonymous 2000a)

Types of applications*	Maximum allowable glyphosate rate ($kg\,ai\,ha^{-1}$)†
Combined total per year for all applications	8.96
Preplant and pre-emergence applications	5.60
Total in-crop application from soybean emergence throughout flowering	3.36
Maximum preharvest application	1.12

* Types of applications include preplant, pre-emergence, at planting, postemergence, preharvest, and postharvest. † Active ingredient in the form of isopropylamine salt of glyphosate.

WEED MANAGEMENT IN GLYPHOSATE-RESISTANT SOYBEAN

Glyphosate application rate and timing

Glyphosate can be applied during the period from soybean emergence to flowering in order to control weeds (Anonymous 2000a). An initial glyphosate (active ingredient in the form of the isopropylamine salt of glyphosate) application of 0.84–1.68 kg active ingredient (ai) ha^{-1} 3–5 weeks after planting provides effective control of most weeds. A sequential (second) application of glyphosate at 0.56–1.12 $kg\,ai\,ha^{-1}$ within 10–14 days after the initial application may be necessary to control later flushes of weeds. Glyphosate can be applied at up to 2.24 $kg\,ai\,ha^{-1}$ in any single application for the control of weeds, where heavy weed densities exist. The glyphosate label specifically limits initial (0.84–2.24 kg $ai\,ha^{-1}$) and sequential (0.56–1.12 $kg\,ai\,ha^{-1}$) applications to less than 3.36 $kg\,ai\,ha^{-1}$ from emergence to flowering in GR soybean (Table 1).

To obtain effective weed control in GR soybean, glyphosate must be applied after most weeds have emerged. The window of application for the initial application of glyphosate postemergence (POST)-only was between the one- to three-trifoliate leaf stages of soybean, or approximately 18–28 days after planting (Swanton *et al.* 2000; VanGessel *et al.* 2000). VanGessel *et al.* (2000) concluded that a delay of application beyond the 4-trifoliate stage gives inconsistent weed control. The effectiveness of glyphosate depends on rate and timing of application relative to weed growth stage. The control of weeds of a given species that differ in size can be attained by simply increasing the rate of glyphosate (Jordan *et al.* 1997). This means that the time of application is of less concern than for other herbicides that have very stringent weed size limitations.

Glyphosate POST-only applications

Glyphosate-resistant soybean offers an option for postemergence (POST) control of broadleaf and grass weeds with glyphosate (Ateh & Harvey 1999; Gonzini *et al.* 1999; Nelson & Renner 1999; Webster *et al.* 1999; Reddy & Whiting 2000; Reddy 2001). The use of a single broad-spectrum herbicide such as glyphosate could eliminate the concern over possible antagonism associated with tank mixes of grass and broadleaf herbicides. Vidrine *et al.* (1995) reported that broadleaf herbicides applied in mixtures were antagonistic toward the activity of certain graminicides. Weeds can be controlled by using a glyphosate POST-only program in GR soybean, thus offering the flexibility to treat weeds on an as-needed basis. Furthermore, because glyphosate has no carryover concern or soil persistence, a glyphosate POST-only program provides farmers with the freedom to choose a rotational crop for the following year without restrictions.

A wide spectrum of weeds was controlled in GR soybean when glyphosate was applied POST. For example, single (1.12 $kg\,ai\,ha^{-1}$ within 4 weeks after planting) or single plus sequential (0.56 $kg\,ai\,ha^{-1}$ at

2 weeks after initial application) glyphosate POST applications provided at least 91% control of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash], browntop millet [*Brachiaria ramosa* (L.) Stapf], hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. *ex* A.W. Hill], pitted morningglory (*Ipomoea lacunosa* L.), prickly sida (*Sida spinosa* L.), sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby], and yellow nutsedge (*Cyperus esculentus* L.) (Reddy 2001; Reddy & Whiting 2000). Weeds such as common waterhemp (*Amaranthus rudis* Sauer); common lambsquarters (*Chenopodium album* L.), entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* Gray), fall panicum (*Panicum dichotomiflorum* Michx.), giant foxtail (*Setaria faberi* Herrm.), johnsongrass [*Sorghum halepense* (L.) Pers.], smooth pigweed (*Amaranthus hybridus* L.), tall morningglory [*Ipomoea purpurea* (L.) Roth], and velvetleaf (*Abutilon theophrasti* Medicus) were effectively controlled with one or two applications of glyphosate (Mckinley *et al*. 1999; Wait *et al*. 1999; Corrigan & Harvey 2000; Culpepper *et al*. 2000). In GR soybean, glyphosate application is an attractive approach for weed management, and several reports have confirmed its efficacy in a wide range of environments.

Glyphosate provides no residual control of weeds. The success of glyphosate in GR soybean depends on the relative growth stage of weeds, weed species, and weather during and after its application. Early season glyphosate application will control weeds that already are emerged, but weeds emerging after application will escape control. Late-season glyphosate application (prior to canopy closure) will control most of the weeds, but delaying too long may result in some weeds being too large to control even with a high glyphosate rate. Therefore, a second application of glyphosate is needed to control problem weeds or to control late emerging weeds.

Relying solely on glyphosate POST applications for timely weed control involves risk (Reddy *et al*. 1999; VanGessel *et al*. 2000). The most critical factor is timing of glyphosate application, which can be affected by weather. In years with heavy rainfall, wet soil can prevent the use of ground equipment for timely glyphosate POST applications. Aerial application of glyphosate is an option, but may be limited by the size of the farm and/or presence of susceptible crops in adjacent fields. Aside from such adverse weather conditions, heavy weed populations, multiple flushes of weed seed germination and establishment, multilayered weed canopies, and a rapidly closing crop canopy can also reduce the efficacy of glyphosate POST programs.

Glyphosate POST applications following pre-emergence herbicide applications

The timing of the first glyphosate application is a critical factor in weed control. Adding a residual pre-emergence (PRE) herbicide at planting generally delays the time the initial glyphosate application is necessary, and also widens the window over which the application can be made. Pre-emergence herbicides reduce detrimental early season weed interference and improve flexibility for the timing of glyphosate POST application. This can benefit producers during extended rainy periods and those who have limited farm equipment. Aside from early season weed control, a PRE herbicide program can create an environment for good soybean stand (population) establishment. However, the PRE herbicide program, which usually consists of a grass and a broadleaf herbicide, costs more than an initial glyphosate POST application. Also, PRE herbicides followed by one application of glyphosate increase herbicide costs compared with two applications of glyphosate (Reddy & Whiting 2000; Reddy 2001). Therefore, the weed control benefit from PRE herbicide programs in GR soybean has to be weighed against the higher herbicide costs compared with the glyphosate POST-only programs. Producers should carefully strive to select a cost-effective herbicide program on an as-needed basis at the individual farm level to maximize yield and net return.

The necessity for PRE herbicides to supplement POST-only programs in GR soybean to maximize weed control, crop yield, and net returns is being investigated by several workers. So far, research has shown that one or two applications of glyphosate can control a broad-spectrum of weed species comparable to PRE herbicides followed by glyphosate (Gonzini *et al*. 1999; Webster *et al*. 1999; Corrigan & Harvey 2000; Culpepper *et al*. 2000; Dirks *et al*. 2000; Reddy & Whiting 2000; Reddy 2001). In all these situations, PRE herbicides were not necessary to supplement total glyphosate POST programs in GR soybean for the control of common weeds.

Glyphosate mixtures with other herbicides

Glyphosate may need a tank-mix partner to control certain problem weeds. Glyphosate mixtures with several POST herbicides have been studied, and the nature of interactions varied from antagonism to synergism, depending upon herbicide chemistry and weed species. Synergistic increase in weed control is the most desirable response, although an additive response may also be beneficial. Glyphosate plus chlorimuron was found to be an additive combination for the control of entireleaf morningglory, pitted morningglory, hemp sesbania, and Palmer amaranth [*Amaranthus palmeri* (S.) Wats.], but the combination was antagonistic for velvetleaf control (Starke & Oliver 1998). Mixing chlorimuron, imazamax, imazaquin, MON 12 000, or pyrithiobac with glyphosate was additive for purple nutsedge and antagonistic for sicklepod control (Rao & Reddy 1999). Glyphosate mixed with bentazon, chlorimuron, pyrithiobac, and imazaquin was antagonistic when applied to redvine [*Brunnichia ovata* (Walt.) Shinners] and trumpetcreeper [*Campsis radicans* (L.) Seem. ex Bureau] (Chachalis *et al.* 2001). Glyphosate plus chlorimuron improved the control of barnyardgrass, hemp sesbania, pitted morningglory, and prickly sida compared with glyphosate alone in narrow-row (19-cm row spacing) GR soybean (Payne & Oliver 2000). Antagonistic interactions were observed in velvetleaf more frequently when chlorimuron, imazethapyr, or thifensulfuron was tank-mixed with glyphosate (Lich *et al.* 1997). Combining herbicides with residual soil activity (e.g. chlorimuron, imazaquin) with glyphosate could prevent late-season weed establishment. Tank-mixtures of herbicides with different modes of action may reduce the selection pressure for the development of glyphosate resistance (Lich *et al.* 1997).

Glyphosate effects on glyphosate-resistant soybean

Although GR soybean is more resistant to glyphosate than non-transgenic soybean, application of glyphosate to some varieties under certain environmental conditions can cause injury, including decreased chlorophyll content in soybean (Pline *et al.* 1999; Reddy *et al.* 2000). Chlorophyll loss in glyphosate-treated GR soybean was rate- and temperature-dependent, with a greater loss at a higher rate and higher temperature (Pline *et al.* 1999). Reddy *et al.* (2000) examined glyphosate effects on glyphosate-resistant soybean varieties under greenhouse conditions. Treatment of GR soybean with glyphosate at 1.12 kg ai ha^{-1} had little or no effect on chlorophyll content and dry weight of shoot and roots in five of five trials. However, treatment with glyphosate at 2.24 kg ai ha^{-1} reduced these parameters in three of five trials, suggesting the potential for soybean injury at higher rates. Application of glyphosate at 1.12 kg ai ha^{-1} 3 weeks after planting had no effect on nodule number or mass, but 2.24 kg ai ha^{-1} reduced these parameters by 30 and 39%, respectively, compared with an untreated control. The leghemoglobin content of nodules was reduced (6–18%) by both glyphosate rates, but effects were inconsistent with these rates.

Currently, hundreds of glyphosate-resistant soybean varieties from different maturity groups are commercially available. The physiological responses of these varieties to glyphosate application may vary, and may also depend on geographical location, environmental conditions, soil types, *Bradyrhizobium japonicum* microbial ecology, etc. This phenomenon needs further investigation. However, most soybean farmers in the midsouthern USA do not use supplemental rhizobium culture or nitrogen fertilizer in soybean production. No yield reductions because of glyphosate applications to GR soybean have been observed in extensive field trials (e.g. Delannay *et al.* 1995; Reddy & Whiting 2000; Elmore *et al.* 2001a; Reddy 2001). Recently, Elmore *et al.* (2001b) have demonstrated that GR sister lines yielded 5% less than the non-GR sisters. The yield suppression appears to be associated with the GR gene or its insertion process rather than glyphosate itself.

OPPORTUNITIES

Control of weeds resistant to other herbicides

There are 153 weed species (91 dicots and 62 monocots) that have evolved resistance to one or more herbicides in 52 countries (Heap 2001). Eighty-six resistant weed biotypes are found in the USA. Glyphosate-resistant soybean offers a tremendous advantage in the management of weeds resistant to other herbicides. Examples are common cocklebur (*Xanthium strumarium* L.) resistant to acetolactate synthatase inhibitors and organoarsenicals, goosegrass [*Eleusine indica* (L.) Gaertn.] resistant to dinitroanilines, horseweed [*Conyza canadensis* (L.) Cronq.] resistant to bipyridiliums, johnsongrass resistant to dinitroanilines and acetyl-CoA carboxylase inhibitors, and pigweeds (*Amaranthus* spp.) resistant to acetolactate synthatase inhibitors.

Reduction in weed control costs

Soybean yields certainly have been variable, but the 20-year trend is upward in the USA (Fig. 2). Soybean prices are at a 20-year low (Fig. 2), while production costs remain at record highs. In this situation, farmers can only survive financially through increasing their production efficiency. This can be done through increased yields, reduced costs, or a combination of the two (Baldwin 2000). If yield levels remain stagnant, then the only way to increase farm profitability is to reduce production costs. One way to reduce production costs is to reduce herbicide usage in order to lower weed control costs. Weed management is one of the most expensive practices in soybean production.

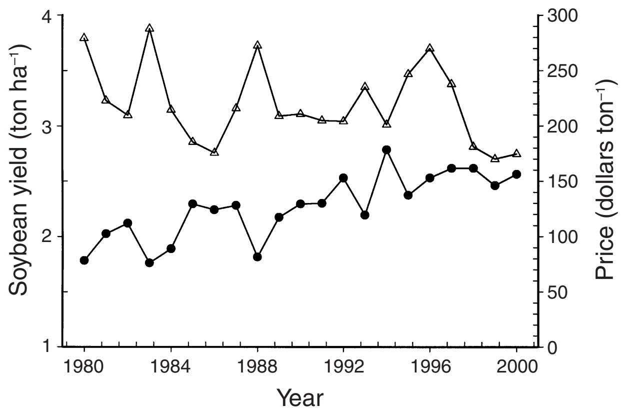

Fig. 2. Trends in the average soybean yields and prices in the USA, 1980–2000 (USDA 2001). (△) Price, (●) yield per hectare.

Herbicide costs still account for more than one-third of total production costs in soybean (Anonymous 2000b). In conventional (non-transgenic) soybean weed control programs, it is not uncommon for a farmer to apply three to five different herbicides. Both PRE and POST herbicides are commonly used to control a broad-spectrum of weeds in conventional soybean. Currently, the total weed control program for conventional soybean with herbicides costs over \$110 per ha (approximately \$55 per ha for each PRE and POST herbicide application) (Anonymous 2000b).

The use of any herbicide technology (e.g. transgenic crops) that includes a fee with the seed purchase must provide an economic benefit over traditional weed control technologies (Reddy *et al.* 1999; Roberts *et al.* 1999; Webster *et al.* 1999; Reddy & Whiting 2000; Reddy 2001). Glyphosate POST-only programs were as profitable in GR soybean as were other herbicide programs in conventional soybean (Reddy & Whiting 2000). Economic benefits of GR soybean can vary considerably depending on variety, year, location, planting condition, and herbicide program. The most notable impact of adopting GR soybean is the reduction in herbicide costs. Glyphosate-based programs are price competitive with existing herbicide programs in conventional soybeans. The introduction of competitively priced glyphosate-based programs resulted in manufacturers of other herbicides dropping their prices, in some cases by 40%. This resulted in an estimated savings of \$216 million in herbicide expenditures for the United States soybean farmers in 1999 compared to 1995, the year before GR soybean was introduced (Carpenter & Gianessi 2001). The estimated savings include the technology fee paid for GR soybean.

Reduction in herbicide use

Herbicide use in soybean has changed dramatically with the introduction of GR soybean. Does the adoption of GR soybean reduce herbicide use? As one would expect, the use of glyphosate has increased with increased GR soybean area. The percentage of soybean area treated with glyphosate increased from 25% in 1996 to 62% in 2000 (USDA 2001). Conversely, the soybean area treated with other herbicides has decreased. For example, imazethapyr-treated areas decreased from 42% in 1996 to 12% in 2000, pendimethalin-treated areas decreased from 28% in 1996 to 11% in 2000, and trifluralin-treated areas decreased from 23% in 1996 to 14% in 2000. There has been a dramatic decrease in the soybean area treated with herbicides that inhibit acetolactate synthatase enzyme, from 86% in 1993 to approximately 43% in 1998 (Shaner 2000). There has also been a decrease in the use of dinitroaniline herbicides, acetyl CoA carboxylase–inhibiting herbicides, and protoporphyrinogen oxidase-inhibiting herbicides (Shaner 2000).

As adoption of GR soybean increased, the average annual rate of glyphosate application increased from 0.19 kg ha^{-1} in 1996 to 0.48 kg ha^{-1} in 1998, while all other herbicides combined dropped from approximately 1.12 kg ha^{-1} to 0.64 kg ha^{-1} (Heimlich *et al.* 2000). This translates to a decline of nearly 10% in the overall rate of herbicide use in soybean during the period. Data also indicates that an adoption of GR soybean led to the substitution of glyphosate for previously used herbicides. Based on a regression analysis in soybean, an estimated 2.5 million kg of glyphosate is substituted for 3.3 million kg of other herbicides, such as imazethapyr, pendimethalin, and trifluralin. In general, herbicides that glyphosate replaced are at least threefold as toxic, and persist in the environment nearly twice as long as glyphosate (Heimlich *et al.* 2000).

CHALLENGES

Glyphosate-resistant soybean should not be relied on to the exclusion of other weed control methods and should be used within integrated weed management systems. Over-reliance on GR soybean could lead to problems such as weed species and population shifts, evolution of glyphosate-resistant weeds, and glyphosate drift. The challenge is for soybean farmers to understand these problems, and for weed scientists to communicate with farmers that continuous use of glyphosate may lead to reduced utility for GR soybean as a weed management tool in the future.

Volunteer plants

Volunteer plants from a previous crop, arising from seed shattering or seeds being dropped during harvest, can become a weed in a succeeding crop. For example, volunteer corn plants in soybean or cotton fields. Control of volunteer transgenic corn in GR soybean can be a serious problem. In a corn–soybean or corn–cotton rotation system, farmers planting GR soybean or cotton after glyphosate-resistant corn will not be able to control volunteer glyphosate-resistant corn with glyphosate. This will require an alternative control strategy such as the use of either a PRE herbicide or another POST herbicide. Also, volunteer plants of one GR soybean variety can be a weed problem in seed production of another GR soybean variety.

Weed species and population shifts

There are certain weed species that are naturally tolerant to glyphosate (see next section). The weed species most likely to increase in frequency in glyphosate-treated fields are those that either have a natural tolerance to glyphosate or are only partially controlled when they are larger at treatment. There has been a report of the lack of control of common cocklebur, common waterhemp, and velvetleaf in Iowa. The lack of control was attributed to the application rate, weed size, environmental conditions, or a combination of these factors. In a field in Iowa, it took three applications of glyphosate to control common waterhemp (Owen 1998).

Based on annual surveys conducted by the Southern Weed Science Society since 1971, Webster & Coble (1997) have well-documented the shifts in relative frequency of weed species as affected by herbicide use patterns in corn, cotton, soybean, and peanut (*Arachis hypogaea* L.). Similarly, continuous use of glyphosate in GR soybean production has the potential to cause weed species shifts. The author is not aware of any published reports on weed species and population shifts caused by repeated applications of glyphosate in GR soybean. Currently, several scientists at universities, the United States Department of Agriculture, and industries are investigating various aspects of GR soybean production that may provide information on long-term implications of using glyphosate in years to come.

Glyphosate-resistant weeds

A few plants species are inherently resistant to glyphosate. A naturally occurring, glyphosate-resistant biotype of field bindweed (*Convolvulus arvensis* L.) has been reported with no history of glyphosate use (DeGennaro & Weller 1984). A biotype of birdsfoot trefoil (*Lotus corniculatus* L.) resistant to labeled glyphosate use rates was identified by Boerboom *et al.* (1990). One potential consequence of continuous use of a single herbicide or herbicides with the same mode of action to control weeds is the selection of resistant weed populations. This has been documented with the selection of triazine-resistant, acetyl CoA carboxylase-inhibitor-resistant, and acetolactate synthatase-inhibitor-resistant weeds (Heap 1997, 2001). Bradshaw *et al.* (1997) opined that unique properties of glyphosate such as its mode of action, metabolism, chemical structure, and lack of residual activity in soil may explain the lack of evolution of weed resistance for glyphosate under field conditions. However, 4 years later, three weed species resistant to glyphosate have been documented (Heap 2001). Evolved resistance to glyphosate in a population of rigid ryegrass (*Lolium rigidum* Gaud.) from an orchard in Australia following two or three applications of glyphosate for 15 years has been documented (Powles *et al.* 1998). Recently, the appearance of glyphosate-resistant goosegrass in Malaysia (Lee & Ngim 2000), rigid ryegrass in South Africa and the USA (Heap 2001), and horseweed in the USA (Heap 2001) also have been reported. These reports of glyphosate-resistant weed species will create doubts about glyphosate as a resistance-free herbicide in the context of intense use of glyphosate for weed control in GR soybean.

In GR soybean, the label accommodates preplant and pre-emergence burndown applications followed by one or two applications of glyphosate in the crop. Thus, a weed population could be exposed to up to 8.96 kg ai ha^{-1} of glyphosate (Table 1) in a year, thus increasing the potential for selection pressure. If glyphosate-resistant corn is accepted as widely as GR soybean has been, then farmers could plant these crops either continuously or in a rotation that makes glyphosate invariably the primary herbicide for multiple years. This will more likely increase the selection pressure on certain weed populations, especially when no PRE herbicides are applied at planting. It must be emphasized that herbicide resistance can be delayed or prevented from occurring, and can be managed when it does occur (Powles *et al.* 1997). Transgenic crops represent a revolutionary breakthrough in weed control technology (Baldwin 2000), and herbicides are a precious resource of great importance to modern agriculture (Powles *et al.* 1997). Therefore, it is equally important that farmers should not completely rely on GR soybean to manage weeds to the exclusion of other herbicides. Farmers must use simple measures, such as the rotation of herbicides from different modes of action (e.g. GR soybean with conventional soybean), or crop rotation with appropriate rotation of herbicides with different modes of action.

Glyphosate drift

In years with heavy rainfall, wet soil can prevent the use of ground equipment for timely applications of glyphosate. Aerial application under these conditions is an option, but there is a potential to damage off-target crops by glyphosate drift. For example, more than 145 drift complaints were filed with the Mississippi Department of Agriculture & Commerce in 2000 because of off-target ground and aerial applications (Anonymous 2001). Most of the 98 complaints investigated were related to the off-target movement of glyphosate. Many of the complaints involved damage to young corn plants caused by glyphosate drift from preplant burndown applications during March and April to adjacent cotton, soybean, or even corn fields. This prompted the Mississippi Department of Agriculture and Commerce to restrict aerial applications of glyphosate, sulfosate, and paraquat in 19 Mississippi counties between 15 March and 30 April of each year, with the exception for emergency applications (Anonymous 2001). However, aerial applications are prohibited when wind velocity exceeds $8\,km\,h^{-1}$ or when other unfavorable conditions such as climatic conditions that create atmospheric inversions exist (Anonymous 2001).

Impact on the development of new herbicides

Currently, there are four major crops (canola, corn, cotton, and soybean) for which glyphosate-resistant varieties are available. Glyphosate-resistant crops have impacted herbicide use. Glyphosate use has increased rapidly with a concomitant decrease in the use of other herbicides. In response to the lower cost of a glyphosate weed control program, other agrochemical industries have decreased the price of their herbicides to remain competitive. Both the herbicide market and profit margin are shrinking. Since the discovery and development of a new compound is expensive, and the new product must be cost-effective to survive in the existing herbicide market, agrochemical industries are reluctant to invest in a shrinking market (Shaner 2000). Currently, there seems to be fewer new herbicides under development. The increased acquisition of seed companies by agrochemical industries and mergers of agrochemical divisions of large companies may reduce the competition for the discovery of new herbicides.

In conclusion, during the past decade, advances in biotechnology have led to the development of herbicide-resistant crops. Genetically engineered soybean via stable integration of a foreign gene allowed the crop to survive glyphosate applications that previously would have killed it. Glyphosate-resistant soybean was commercialized in the USA in 1996, and by 2001, nearly 70% of the United States soybean area was planted with GR soybean. The rapid acceptance of GR soybean by the American farmers is because of several reasons: simplicity of weed control program; one herbicide controls a broad spectrum of broadleaf, grass, and sedge weeds; flexibility in glyphosate application rate (depending on weed species and growth stage), and timing (soybean emergence to flowering stage); lower herbicide cost; and no crop rotation restrictions. In contrast, in conventional soybean weed control programs, it is not uncommon for a farmer to apply 3–5 different herbicides to manage weeds. An over-reliance on glyphosate for weed control in GR soybean monocrop, or in rotation with other GR crops (e.g. corn, cotton), may increase the potential for shifts in weed species and selection of resistant weed populations. Thus, prudent use of a GR soybean system in combination with other weed control methods will most likely prolong its use as a weed management tool. Glyphosate-resistant soybean is not commercially grown in Europe, Japan, and many other countries because of the fear of consumers against possible adverse effects of genetically modified organisms on the environment and human health. Increased consumer confidence in genetically modified organisms in these countries is critical for the adoption of GR soybean as a weed management tool.

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DISCLAIMER

The mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the United States Department of Agriculture, and does not imply their approval to the exclusion of other products that may also be suitable.

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