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A Grower Survey of Herbicide Use Patterns in Glyphosate-Resistant Cropping Systems

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A telephone survey was conducted with growers in Iowa, Illinois, Indiana, Nebraska, Mississippi, and North Carolina to discern the utilization of the glyphosate-resistant (GR) trait in crop rotations, weed pressure, tillage practices, herbicide use, and perception of GR weeds. This paper focuses on survey results regarding herbicide decisions made during the 2005 cropping season. Less than 20% of the respondents made fall herbicide applications. The most frequently used herbicides for fall applications were 2,4-D and glyphosate, and these herbicides were also the most frequently used for preplant burndown weed control in the spring. Atrazine and acetochlor were frequently used in rotations containing GR corn. As expected, crop rotations using a GR crop had a high percentage of respondents that made one to three POST applications of glyphosate per year. GR corn, GR cotton, and non-GR crops had the highest percentage of growers applying non-glyphosate herbicides during the 2005 growing season. A crop rotation containing GR soybean had the greatest negative impact on non-glyphosate use. Overall, glyphosate use has continued to increase, with concomitant decreases in utilization of other herbicides.

Nomenclature: 2,4-D; acetochlor; atrazine; glyphosate; corn, *Zea mays* L.; cotton, *Gossipium hirsutum* L.; soybean, *Glycine max* (L.) Merr.

Key words: Postemergence, preemergence, preplant burndown, soil residual herbicides, tank mixtures, weed management.

The introduction of 2,4-D in the mid-1940s ushered in a new era in which growers had a viable alternative to mechanical control of weeds (Burnside 1996). Over the following decades, there was an explosion of herbicide discovery that changed the way growers managed weeds. During this time of herbicide discovery, several nonselective herbicides were commercialized, including paraquat, glufosinate, and glyphosate.

Glyphosate was introduced to the market in the early 1970s for broad spectrum weed control, including perennial weeds. Glyphosate has become one of the world's leading agrochemicals (Woodburn 2000). During the 1970s and early 1980s, research explored means of breeding herbicide resistance into crops (Barrentine et al. 1982). However, it was not until the 1980s that the tools for developing genetically engineered, transgenic crops became available. Several companies saw the advantage of using these technologies to produce transgenic crops that would be resistant to herbicides. Extensive efforts were put forth to develop GR crops, eventually leading to the use of the CP4 gene from *Agrobacterium* sp. This gene codes for a glyphosate-insensitive 5-enol-pyruvylshikimate-3-phosphate synthase (EPSPS) in selected crops (Padgette et al. 1995).

The first commercially available GR crop was soybean, introduced in 1996. GR cotton followed in 1997, and GR corn was introduced in 1998. In 2007, 91% of soybean, 70% of cotton, and 52% of the corn hectares were planted to GR cultivars in the United States (USDA-NASS 2007). Adoption of GR technologies has been rapid due to a wider spectrum of weeds controlled, less need for tank-mixing other herbicides, and reduced time and labor inputs (Ateh and Harvey 1999; Bradley et al. 2004; Corbett et al. 2004; Faircloth et al. 2001; Johnson et al. 2000; Reddy and Whiting 2000; Thomas et al. 2004a, b).

After nearly a decade of growing GR crops one would expect significant changes in herbicide use in terms of the frequency and amount of use for herbicide active ingredients. Several researchers have investigated herbicide use patterns following GR crop adoption by examining existing datasets such as the National Agricultural Statistics Service (NASS) chemical use databases and other industry compiled databases (Shaner 2000; Young 2006). An overall reduction in the amount of herbicides applied was noted since grower adoption of GR cropping systems, as was an increased reliance on glyphosate in their weed management programs.

One means of collecting data on actual usage and grower perceptions about weed management is through grower surveys. These surveys have been used in the past to document changes in management practices and grower perceptions about potential problems in a wide range of areas from irrigation practices to perceptions about insect pressure and pesticide use (Dillard 1993; Snyder 1996). Grower surveys have been especially important to weed science and have allowed scientists to gain insight into a number of grower perceptions and practices. Examples include herbicide and herbicide-resistant crop use and grower perceptions of issues such as herbicide resistance in weeds (Charles 1991; Gibson et al. 2005; Gibson et al. 2006; Johnson and Gibson 2006; Llewellyn et al. 2002). By using grower surveys, we have the opportunity to capture a cross-section of weed management

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Table 1. Herbicide application summary for all reported crop rotations in Iowa, Illinois, Indiana, Mississippi, North Carolina, and Nebraska for the 2005 growing season. The responses are categorized by application timing.

			Glyphosate applications				Non-glyphosate applications				
Crop rotation	Fall application of herbicides	Burndown application prior to or at planting in the spring	1 application	2 applications	> 3 applications	Did not apply	Prior to planting	At planting	Post emerge	Did not apply	Avg. no. yrs. an herbicide other than glyphosate was applied[b]
	% of growers making each application										
Continuous GR[a] corn											
(n = 84)	13	27	54	42	2	1	12	16	24	57	1.3
Continuous GR soybean											
(n = 307)	14	60	23	62	12	2	4	1	10	85	0.7
Continuous GR cotton											
(n = 97)	10	76	12	44	42	–	10	10	69	36	2.1
GR corn / GR soybean											
GR corn (n = 407)	7	36	63	32	2	3	18	20	13	56	1.2
GR soybean (n = 407)	9	38	48	47	3	2	9	2	6	84	0.9
GR cotton / GR Soybean											
GR cotton (n = 38)	16	76	18	47	29	–	3	5	58	47	1.6
GR soybean (n = 38)	8	63	26	53	13	3	5	–	16	79	1.1
GR soybean/on-GR crop											
GR soybean (n = 496)	8	42	52	43	4	1	11	2	8	81	1.3
Non-GR crop (n = 496)	6	27	–	–	–	–	22	46	53	23	1.9
GR corn / non-GR crop											
GR corn (n = 85)	14	25	61	31	2	6	17	25	20	45	1.8
Non-GR crop (n = 85)	4	20	–	–	–	–	12	31	53	33	1.5

[a] Abbreviations: GR, glyphosate-resistant.

[b] Average number of years non-glyphosate herbicide was applied (out of the last 3 yr).

practices and their potential problems spanning different states and crop rotations after using a GR crop.

The purpose of this paper is to determine and quantify the effect of GR crop use on growers' herbicide use patterns. The data for this paper are a subset from a dataset generated from a telephone survey that was conducted between November 9, 2005 and January 6, 2006, to capture many aspects of long-term GR crop use and the changes over time that have occurred because of their use.

Materials and Methods

A survey was designed by the authors and conducted in six states. The telephone survey was conducted by contacting growers from Iowa, Illinois, Indiana, Mississippi, North Carolina, and Nebraska. A list of all growers from these states who had signed an agreement to use the glyphosate-resistant crop [Roundup Ready™] technology was obtained from the company, and survey respondents were randomly selected from this list. Respondents were initially asked whether they were actively involved in farming, if they were responsible for the management decisions in their farming operations, if they planted a minimum of 101 hectares of corn, soybean, or cotton in 2005, and if they planted one of the traits or trait combinations for a minimum of 3 yr. Producers were disqualified from the survey if they or anyone in their household worked for a farm chemical manufacturer, distributor, or retailer, or if they worked for a seed company other than as a farmer/dealer. The survey consisted of four sections dealing with different aspects of their farming practices. The sections dealt specifically with cropping history, weed pressure and tillage practices, herbicide use, and GR weeds. The respondents were asked to focus their answers on one specific representative field for each cropping system. Complete details of the survey are reported in an introductory paper for this series by Shaw et al. (2009). This paper will focus mainly on the herbicide use data generated from the survey.

For this analysis, only the following crop rotations are discussed: continuous GR corn, continuous GR soybean, continuous GR cotton, GR corn / GR soybean rotation, GR cotton / GR soybean rotation, GR soybean / non-GR crop rotation, and GR corn / non-GR crop rotation. Grower responses on herbicide application timing and frequency within each cropping system are located in Table 1. Table 2 lists the most frequently used herbicide active ingredients for fall applications. Table 3 lists the herbicide active ingredients used for preplant burndown applications. Data presented in Table 4 are the applications of non-glyphosate herbicide active ingredients pooled across application timings and the percentage of growers in each crop rotation that did not apply an herbicide other than glyphosate during the cropping season in question.

Results and Discussion

The data presented in Table 1 are a summary of responses to the questions relating to herbicide use. The data are categorized by crop rotation and herbicide system. The crop rotations examined included continuous GR corn, continuous GR cotton, continuous GR soybean, GR corn / GR soybean, GR cotton / GR soybean, GR soybean / non-GR crop, and GR corn / non-GR crop. The herbicide systems were broken out by fall application, preplant burndown application, glyphosate–in-crop applications, and non-glyphosate–in-crop applications. Glyphosate applications were further categorized

Table 2. Fall herbicides applied for each crop rotation. Data expressed as percentages of producers in each crop rotation who applied each herbicide.

Crop rotation	Atrazine	Simazine	Chlorimuron	Flumioxazin	Glyphosate	2,4-D	Dicamba	Paraquat
	% of growers making each application							
Continuous GR[a] corn (n = 11)	–	–	–	–	36	9	–	–
Continuous GR soybean (n = 43)	–	–	5	–	56	7	5	5
Continuous GR cotton (n = 10)	–	–	–	–	30	–	–	–
GR corn / GR soybean								
GR corn (n = 30)	10	17	3	–	16	13	–	–
GR soybean (n = 37)	–	3	27	–	27	19	–	–
GR cotton / GR soybean								
GR cotton (n = 0)	–	–	–	–	–	–	–	–
GR soybean (n = 0)	–	–	–	–	–	–	–	–
GR soybean / non-GR crop								
GR soybean (n = 41)	–	2	37	5	32	32	–	–
Non-GR crop (n = 31)	10	26	–	–	10	16	–	–
GR corn / non-GR crop								
GR corn (n = 12)	17	–	–	–	25	25	–	–
Non-GR crop (n = 0)	–	–	–	–	–	–	–	–

[a] Abbreviations: GR, glyphosate-resistant.

by number of applications, and non-glyphosate applications were further categorized by timing of the applications. Data from each application timing category are discussed below.

Fall Herbicide Use. Between 4 and 16% of growers made fall applications of herbicides prior to planting the specified crop in 2005 (Table 1). Four to 6% of the respondents indicated they used a fall herbicide application prior to planting a non-GR crop. Conversely, at least 10% of the growers with crop rotations that included continuous GR corn, continuous GR soybean, and continuous GR cotton used a fall herbicide application. Thus, the use of fall herbicide application may be more common in continuous GR cropping systems. The cause of the increased need for fall herbicide applications in continuous GR cropping systems is beyond the scope of this survey. However, greater reliance on glyphosate and non-residual herbicides has been associated with greater problems with winter annual weeds. The most commonly used herbicides across all crop rotations were glyphosate and 2,4-D (Table 2). Atrazine, chlorimuron, and simazine were also frequently used herbicides, but their usage was very specific, based on crop tolerances of each rotation. These herbicides are often applied in the fall to control weeds that would otherwise be difficult to manage in the spring and potentially compete with the crop (Wicks et al. 2000).

Preplant Burndown Herbicide Use. Between 20 and 76% of growers used a preplant burndown application (Table 1). Similar to fall herbicide use, the most frequently used herbicides for spring preplant burndown applications across all crop rotations were glyphosate and 2,4-D (Table 3). Furthermore, the use of glyphosate was often four to six times more frequent than 2,4-D, depending on the specific crop rotation. The most frequently used crop-specific herbicides were atrazine and acetochlor in rotations containing corn. In these rotations, glyphosate and 2,4-D were used in preplant burndown applications. A higher percentage of growers in a crop rotation that included GR cotton or GR soybean used glyphosate in their preplant burndown herbicide applications, particularly the growers in the GR cotton / GR soybean rotation. Glyphosate and glyphosate / 2,4-D combinations are effective herbicides for controlling winter annual weeds, and

Table 3. Herbicide applied as preplant burndown for each crop rotation. Data expressed as percentages of producers in each crop rotation who applied each herbicide.

Crop rotation	Atrazine	Acetochlor	Pendimethalin	Isoxaflutole	Glyphosate	2,4-D	Paraquat
	% of growers making each application						
Continuous GR[a] corn (n = 23)	22	17	–	–	52	13	–
Continuous GR soybean (n = 183)	–	–	1	–	76	20	–
Continuous GR cotton (n = 74)	–	–	5	–	90	15	–
GR corn / GR soybean							
GR corn (n = 147)	15	13	–	–	40	16	5
GR soybean (n = 155)	–	–	–	–	63	16	2
GR cotton / GR soybean							
GR cotton (n = 29)	–	–	–	–	86	–	–
GR soybean (n = 24)	–	–	–	–	92	–	–
GR soybean / non-GR crop							
GR soybean (n = 41)	–	–	–	–	69	20	1
Non-GR crop (n = 31)	8	–	–	5	48	21	8
GR corn / non-GR crop							
GR corn (n = 21)	10	10	–	–	14	24	–
Non-GR crop (n = 17)	–	–	–	–	59	12	–

[a] Abbreviations: GR, glyphosate-resistant.

Table 4. Non-glyphosate herbicides applied for each crop rotation. Data expressed as percentages of producers in each crop rotation who applied each herbicide.

Crop rotation	Non-glyphosate herbicides applied
	% of growers making each application
Continuous GR corn (*n* = 36)	47% atrazine
	25% acetochlor
	8% simazine
	6% *s*-metolachlor
Continuous GR soybean (*n* = 46)	26% chlorimuron
	13% flumiclorac
	9% 2,4-D
	2% *s*-metolachlor
	2% pendimethalin
	2% flumioxazin
Continuous GR cotton (*n* = 62)	27% diuron
	19% pyrithiobac
	15% MSMA
	15% trifloxysulfuron
	12% prometryn
	11% pendimethalin
	8% flumioxazin
	8% fluometuron
	8% *s*-metolachlor
	2% 2,4-D
GR corn / GR soybean	
GR corn (*n* = 181)	33% atrazine
	28% acetochlor
	7% *s*-metolachlor
	5% 2,4-D
GR soybean (*n* = 67)	15% pendimethalin
	11% imazethapyr
	9% chlorimuron
	8% *s*-metolachlor
	6% acetochlor
	6% clethodim
	5% 2,4-D
	5% flumioxazin
GR Cotton / GR Soybean	
GR cotton (*n* = 20)	20% MSMA
	20% *s*-metolachlor
	20% trifloxysulfuron
	10% prometryn
	15% flumioxazin
	10% fluometuron
GR soybean (*n* = *0*)	—
GR soybean / non-GR crop	
GR soybean (*n* = 94)	15% pendimethalin
	11% 2,4-D
	9% trifluralin
	7% cloransulam
	6% imazethapyr
	5% flumiclorac
	1% acetochlor
	1% nicosulfuron
	1% *s*-metolachlor
Non-GR crop (*n* = 384)	20% atrazine
	20% *s*-metolachlor
	13% mesotrione
	12% acetochlor
	7% 2,4-D
	7% isoxaflutole
	6% clopyralid
	6% nicosulfuron
	2% pendimethalin
	1% trifluralin
	< 1% cloransulam
GR corn / non-GR crop	
GR corn (*n* = 47)	32% atrazine
	28% acetochlor
	13% *s*-metolachlor
	4% mesotrione
	2% glufosinate
Non-GR crop (*n* = 57)	16% *s*-metolachlor
	11% 2,4-D
	10% acetochlor
	9% atrazine
	9% mesotrione
	5% glufosinate

the herbicides' relatively low cost makes them attractive options for growers. The usage of glyphosate and 2,4-D is slightly lower for rotations including GR corn, suggesting the utilization of other herbicides. The data in Table 3 support this, showing that herbicides such as atrazine and acetochlor were used in rotations that included GR corn. Johnson et al. (2000) also found that by using glyphosate along with reduced rates of chloroacetamide (acetochlor) or triazine (atrazine) herbicides provided better control of weed species than full rates of chloroacetamide or triazine herbicides without the addition of glyphosate.

Postemergence Glyphosate Use. Most growers applied two or fewer postemergence applications of glyphosate during crop growth (Table 1). However, in crop rotations that include GR cotton, 30 to 40% of the growers made three applications of glyphosate. Prior to GR cotton, preemergence and postemergence-directed herbicide applications or cultivation were used to control weeds in cotton (Culpepper and York 1998; Snipes and Mueller 1992a, b; Wilcut et al. 1995). Since the commercialization of GR cotton, more and more growers have moved toward total postemergence weed control programs. Reasons for this change include the lack of herbicides labeled for preplant or preemergence use, the difficulty in obtaining adequate height differential between crops and weeds for postemergence-directed applications, marginal crop tolerance to many of these herbicides, and the specialized equipment needed to make these applications (Askew and Wilcut 1999; Culpepper and York 1999; Snipes and Mueller 1992a, b; Wilcut et al. 1997). The main drawback to a total postemergence program using glyphosate is the lack of residual weed control from glyphosate. Multiple applications of glyphosate to the cotton crop are needed to obtain satisfactory weed control if no other weed control tactics are used.

Two or more postemergence applications of glyphosate in GR soybean were used by 66 to 74% of the growers in a continuous GR soybean or GR cotton / GR soybean cropping system (Table 1). However, only 47 to 50% of the growers used two or more postemergence applications of glyphosate in a GR corn / GR soybean or GR soybean / non-GR crop rotation. Of the growers in continuous GR soybean production, 62% required at least two postemergence applications of glyphosate (Table 1). Of the growers that had GR in their crop rotation, 43 to 53% of them made at least two applications of glyphosate. The tendency to use fewer postemergence applications of glyphosate may be a function of the soybean row spacing, planting date, or geography (soybean maturity length, duration of crop growth). Soybean weed control programs were dominated by imidazolinones and dinitroaniline herbicides from 1992 to 1996, prior to the introduction of GR soybean. With the introduction of GR soybean, many producers began to rely exclusively on glyphosate for weed management (Young 2006). Another reason for the heavy use of glyphosate in GR soybean is that it fills in the gaps left by many conventional soybean weed management programs (Gianessi 2005).

In GR corn, 31 to 44% of the growers used two postemergence applications of glyphosate, which is relatively less than the frequency of glyphosate use in GR soybean or GR cotton (Table 1). The historical availability of cost-effective non-glyphosate products in corn may partially explain the difference in glyphosate use between crops. For example, atrazine in combination with *s*-metolachlor provides, in most cases, economical, season-long weed control (Thomas et al. 2007). Another reason is the rate of GR corn adoption has been slower than the rate of GR soybean or GR cotton (Johnson and Gibson 2006). The GR trait until recently has not been available in many of the most popular corn hybrids. Glyphosate applications in GR corn can only be made up until the V8 crop stage, or until the crop reaches 76 cm in height (Anonymous 2007). For GR soybean, glyphosate applications can be made up until flowering (R2 stage) (Anonymous 2007). This narrow application window for GR corn may also be a contributing factor to the low adoption of GR corn. Gianessi (2005) found that most corn growers who have adopted GR corn technology have done so because they have difficult-to-control weed problems that necessitate more costly herbicide programs. The work of Johnson et al. (2000) found that the use of glyphosate and atrazine or acetochlor provides better control than the use of glyphosate alone.

Non-Glyphosate Herbicide Use. Growers more frequently utilized a non-glyphosate herbicide prior to planting (12 to 18%) and at planting (16 to 25%) in the production of GR corn (Table 1). Corn producers still rely on soil-applied herbicides such as atrazine as the foundation of their weed control programs. Reasons for this are discussed above.

A lower percentage of growers applied non-glyphosate herbicides prior to rotations that included GR soybean or GR cotton (3 to 11%). Common herbicides used prior to planting included diuron, fluometuron, pendimethalin, *s*-metolachlor, and trifluralin. These were commonly used herbicides in weed management programs prior to the development of GR cotton and GR soybean (Young 2006).

During the postemergence timing, rotations that included GR cotton and non-GR crops had 53 to 69% using non-glyphosate herbicides. The herbicides prometryn, pyrithiobac-sodium, MSMA, and trifloxysulfuron are still utilized in cotton for over-the-top and layby applications to achieve satisfactory weed control (Table 4). However only prometryn, pyrithiobac, MSMA, and trifloxysulfuron are commonly used. The herbicide use pattern may change with the release of new GR cotton cultivars in 2006 that allow for later postemergence applications of glyphosate (Huff et al. 2007). Prior to the release of the enhanced GR cotton trait, glyphosate applications were limited to the four-leaf stage in cotton. Applications later than this could result in fruit abortion and yield reduction (Viator et al. 2003, 2004). With the introduction of enhanced GR cotton in 2006, glyphosate applications are possible from crop emergence until 7 d prior to harvest (Anonymous 2007).

The non-GR crops in the crop rotations included conventional corn, soybean, and rice (*Oryza sativa* L.). For these crops, traditional postemergence weed management practices, such as those herbicides listed in Table 4, are used to achieve acceptable weed control.

During the 2005 growing season, 79 and 85% of the producers in GR soybean did not apply a non-glyphosate herbicide (Table 1). These results are in agreement with the findings of Shaner (2000), who found a decrease in the use of ALS inhibitors, acetyl CoA carboxylase (AACase) inhibitors and protoporphyrinogen oxidase (PPO) inhibitors in soybean since 1993. Gianessi (2005) found that one glyphosate application in some cases substituted for three to four herbicides, often applied separately, with the potential need for tillage to obtain adequate weed control. Glyphosate-based weed control programs are inexpensive, convenient and, given the market value of soybean over the past couple of years, a very attractive option for producers.

Results from this survey show that in most instances non-glyphosate–herbicide based weed management programs have been (GR cotton and GR soybean) or are in the process of being (GR corn) replaced with glyphosate as the core, or sole, herbicide. The longer a GR crop is available to producers, and as GR technology develops and advances, these glyphosate-based weed management programs become more attractive to producers. This trend has been especially evident in GR soybean, which has been available for 11 yr, and for which herbicide-use patterns have progressively moved toward intensive glyphosate programs. Now that new GR technology for cotton is available, and allowing for later applications of glyphosate, one can deduce that this trend will become apparent in GR cotton production as well. The same might be said of GR corn production as the technology matures. Adoption of GR corn in the United States has been slower, due again to several factors. Excellent efficacy of existing herbicide programs, as discussed before, may be a contributing factor. Another factor is that GR corn varieties have not been approved for import into Europe (Gianessi 2005). There has been limited information on the efficacy and economics of GR corn (Thomas et al. 2004a), although current research is addressing this deficit (Gianessi 2005; Johnson et al. 2000; Thomas et al. 2004a, b). The increased interest of domestic ethanol production may address export concerns as more corn is used for ethanol production in the United States.

Researchers have also begun to study the possible adverse effects of weed management systems relying exclusively on glyphosate. Weed shifts and acceleration of glyphosate resistance in weeds are some of the top concerns with these systems (Duke 2005; Shaner 2000; Young 2006). Due to concerns about glyphosate resistance, as well as a number of other management and economic factors, anecdotal data indicate there may be shifts toward greater utilization of soil-applied herbicides. Thus, a follow-up survey will be of great interest to determine why any shifts in herbicide use patterns may continue to occur.

Grower surveys are a valuable tool for documenting herbicide use patterns and the grower attitudes and perceptions driving decisions regarding herbicide selection. The data from this survey will be invaluable reference material for weed scientists and agricultural analysts in understanding the level of glyphosate herbicide usage, the other primary herbicide tools being utilized, and the current benchmarks for herbicide usage in GR crops. As changes continue to occur in herbicide programs, these data will serve as an important snapshot in time for future reference.

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