ECONOMIC INCENTIVES AND RESISTANCE MANAGEMENT

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Abstract

Since the commercial introduction of transgenic, herbicide-resistant cultivars, the diversity of weed control tactics used in cotton, soybeans, and corn has declined considerably. Increased reliance on a narrow range of tactics and herbicide mechanisms of action has contributed to a predictable rise in the incidence of weed resistance to herbicides. Many growers have adopted many best management practices (BMPs) to delay resistance. However, data suggest that most growers are not adopting those BMPs most crucial for successful resistance management, particularly use of multiple herbicides expressing diverse mechanisms of action. This study provides an overview of sources of survey data concerning weed resistance management and summarizes the main findings regarding grower adoption of BMPs. This summary provides a baseline of information characterizing grower perceptions about herbicide resistance and adoption of BMPs as of the mid-2000s. Next, it introduces a dynamic weed-management model to illustrate the role of economic incentives for herbicide resistance management. It concludes by examining economic factors that can constrain BMP adoption and discusses policy options to align private incentives for resistance management with the social objective of preserving the effectiveness of weed control strategies.

Introduction

Genetically modified (GM) glyphosate-resistant (GR) soybean and corn were commercially introduced 1996, with GR cotton introduced in 1997. GR seed varieties now dominate total acreage of each crop. While crops with herbicide-resistant (HR) traits have provided significant economic and environmental benefits, these benefits are threatened by the evolution of weed resistance. The evolution of HR weeds threatens the sustainability of these benefits, however. The number and range of glyphosate-resistant weeds has been increasing in the United States since commercialization of GR crops (Heap, 2009). The evolution of weed resistance to herbicides also poses problems for other herbicide-resistant crops, such as LibertyLink® or Clearfield® crops.

The potential for weeds to develop resistance in response to frequent applications of a narrow set of chemicals with the same mechanism of action is well established (Holt and Lebaron, 1990; Powles and Shaner, 2001; Shaner, 1995). Beckie (2006, pp. 793) identifies, "recurrent application of highly efficacious herbicides with the same site of action" and "annual weed species that occur in high population densities" as key risk factors for the evolution of herbicide resistance in weeds. However, strategies for reducing the risk of weed resistance are also well documented (e.g. see Burgos et al., 2006). Commodity groups, extension specialists, and agricultural chemical and seed companies have recommended that growers adopt various best management practices (BMPs) to prevent or delay the spread of HR weeds. These strategies include weed scouting; avoidance on over-reliance on a compound or compounds with a single mechanism of action against weeds; preventing herbicide-resistant gene spread, non-chemical control such as tillage, and crop rotations. A key element of this strategy is diversifying weed management tactics. Since the commercial introduction of GM, HR cultivars, the diversity of weed control tactics used in cotton, soybeans, and corn has declined considerably, however. Increased reliance on a narrow range of tactics and herbicide mechanisms of action has contributed to a predictable rise in the incidence of weed resistance. This study provides an overview of sources of survey data concerning weed resistance management and summarizes the main findings regarding grower adoption of BMPs. This summary provides a baseline of information characterizing grower perceptions about herbicide resistance and adoption of BMPs as of the mid-2000s. Next, it introduces a dynamic weed-management model to illustrate the role of economic incentives for herbicide resistance management. It concludes by examining economic factors that can constrain BMP adoption and discusses policy options to align private incentives for resistance management with the social objective of preserving the effectiveness of weed control strategies.

Data Sources Concerning Weed Resistance Management

One may divide data and information concerning weed resistance management into three categories. The first are periodic USDA surveys of herbicide use and cropping practices (including weed management). Data collection is national in scope, focusing on major producing states of different crops. These surveys collect data over multiple years, facilitating analysis of trends in weed management and herbicide use. While not designed to examine resistance management specifically, these surveys provide useful indicators of adoption of some BMPs. The Agricultural *Chemical Usage – Field Crops* report published by USDA, NASS (downloadable at http://www.nass.usda.gov/QuickStats/Create_Federal_All.jsp) reports on acres treated by individual herbicides, average number of treatments, pounds of active ingredient (a.i.) per application and total pounds of a.i. applied. These data are relevant for evaluating trends in diversification and concentration in herbicide mechanism of action.

Crop Production Practices data files are available from USDA's Economic Research Service (ERS) (http://www.ers.usda.gov/Data/ARMS/app/default.aspx?survey_abb=CROP). ERS provides a web-based query system allowing cropping practices data to be organized and downloaded. Data come from Phase II of the Agricultural Resource Management Survey (ARMS), USDA's primary source of information about production practices for corn, soybeans, cotton, and other major crops. While ARMS has not explicitly asked question about resistance or resistance management, it does provide data related to several BMPs. These include: (a) weed scouting; (b) pre- and post-emergence herbicide applications; (c) applications by herbicide family; (d) tillage practices; and (e) cultural management techniques such as crop rotations, seeding rates, and row spacing. The downloadable ARMS data reports weed management practices aggregated by state or region. This limits inferences one can make about BMP adoption. Farm-level survey responses have the potential to provide a richer understanding of how weed management practices conform to recommended BMPs. Access to the farm-level data is restricted, requiring a memorandum of understanding between research institutions and USDA. Neither the Chemical Usage nor the ARMS data are current. The most recent chemical usage data are from 2005 for corn and cotton and 2006 for soybeans. The most recent ARMS Phase II survey years were 2005 for corn, 2006 for soybeans, and 2007 for cotton. New ARMS data were collected for corn and cotton in 2010, but data are not yet available.

Industry-sponsored, multi-state surveys provide a second source of data. These include telephone surveys of corn, soybean, and cotton growers:

(a) A Monsanto-supported survey of 1,195 growers in six states (IL, IA, IN, NE, MS, NC) between November 2005 and January 2006, known as the Benchmark Study (Shaw et al., 2009);
(b) A Syngenta-supported survey of 400 growers in the Corn and Cotton Belts in Spring 2006 (Foresman and Glasgow, 2008);
(c) A Monsanto-supported survey of 1,205 growers across the Southern Plains, Northern Plains, Corn Belt, Lake States, Delta, and Southeast in Winter 2007 (Frisvold et al., 2009);
(d) Data collected from 2006-8 as a follow-on to the Benchmark Study to assess the effect of academic-recommended BMPs on weed populations, diversity, seedbank, crop yields, production costs, and net economic returns (Shaw et al., 2011).

These surveys ask questions more directly related to weed resistance and BMP adoption than the USDA surveys. Although survey regions, emphases, and questions differ across studies, many findings are comparable. One limitation of these studies is that they omit smaller-scale producers (usually those with fewer than 250 acres) of the target crops in the survey. Although such small-scale producers account for a minority of corn, soybean, and cotton acreage, they comprise the majority of the growers of these crops. These surveys thus cannot provide information about whether this group differs significantly from larger scale operators or if they pose any special challenges for managing resistance.

Third, one can also obtain useful information from smaller-scale weed management surveys (Johnson and Gibson, 2006; Wilson, et al., 2008; Harrington, 2009). In addition, research from Australia reinforces some findings in the United States (e.g. Llewellyn et al., 2002; Llewellyn and Allen, 2006). These studies are even more diverse in terms of questions asked than the industry-sponsored studies.

NASS Chemical Usage Survey Findings

The development of GR crops transformed glyphosate from an herbicide primarily used for non-crop and perennial crop weed control to the dominant herbicide used in-season for cotton and soybean production. Soybean acres treated with glyphosate rose from 20% to 95% from 1995 to 2006, while cotton acres treated with glyphosate rose from 9% to 74% from 1995 to 2005 (Table 1). Glyphosate accounted for 89% pounds of herbicide a.i. applied to soybeans in 2006 and 57% of pounds of herbicide a.i. applied to cotton in 2005. As of 2005, use of glyphosate had not become dominant in corn production, perhaps because of the slower adoption of GR corn. Nevertheless, the share of acres treated grew from 4% to 33% from 1997 to 2005. Glyphosate's share of all herbicide pounds of a.i. applied to corn rose from 1% in 1997 to 15% in 2005.

Table 1. National trends in glyphosate use for U.S. corn, soybeans, and cotton.

Crop	Year	Acres treated with glyphosate (%)	Glyphosate pounds of active ingredient (a.i.) applied as a % of total pounds of herbicide a.i. applied
Corn	1997	4	1
	1999	9	3
	2005	33	15
Soybeans	1995	20	11
	1999	62	54
	2006	95	89
Cotton	1995	9	3
	1999	36	20
	2005	74	57

Source: USDA, NASS Chemical Usage Survey – Field Crops

USARMS Findings

The range of herbicides used on a crop provides one indicator of the diversity of weed management programs. Table 2 lists the major herbicide families, and their mechanism of action (MOA), used in corn, soybean, and cotton production. It compares 1996 with years of the most recent ARMS data for each crop. For all three crops, there has been a reduction in the diversity of herbicides used and the mechanisms of action employed between the earlier and later dates. Glyphosate (a phosphinic acid herbicide and enolpyruvyl shikimate-3-phospate synthase inhibitor) has grown to dominate in soybeans and cotton. Over this time, use of several herbicide families has ceased or been dramatically reduced. Three factors contributed to reliance on a relatively few mechanisms of herbicide action. First, there was increasing incidence and distribution of resistance to mechanisms of action that had been in general use for a long time, notably the acetolactate synthesase (ALS – B2) and Photosystem II (Cs) herbicides. Second, glyphosate became attractive as a post-emergence herbicide because of its broad-spectrum efficacy and reliability. Low cost was also a factor after the patent on glyphosate expired in 2000 (allowing lower cost generics on the market). Third, herbicides with new mechanisms of action have not been registered in the United States since 1993. Phosphinic acid herbicides accounted for 60% of acre treatments for cotton in 2007 and 77% of acre treatments for soybeans in 2006. By 2005, triazine and phosphinic acid treatments in corn accounted for two-thirds of acre treatments. Use of several herbicide families, such as the amides, benzoic, and the sulfonylureas, sharply declined between 1996 and 2005. Overall, there is a narrowing of herbicides and herbicide mechanisms of action for all three crops. The heavy use of a single MOA on in these crops is contrary to herbicide resistance management as it greatly increases the selection pressure for resistance to this MOA.

Table 3 reports ARMS data for national trends in some weed management indicators. For all three crops, the data show: (a) the rapid adoption of genetically modified (GM) herbicide resistant (HR) seed varieties, especially for soybeans (97% of acreage) and cotton (90% of acreage); (b) a modest increase in the rate of field scouting for weeds; (c) increased reliance on post-emergence weed control and decreased reliance on pre-emergence weed control; (d) reduced reliance on cultivation for weed control; and (e) increased reliance on burndown herbicides in soybeans and cotton.

Table 2. Herbicides, by herbicide family, applied to corn, soybean and cotton acres.

Herbicide family	Mechanism of action [1]	Percent of total herbicide acre-treatments by survey year	
Corn		1996	2005
Phosphinic acid	$G^{(9)}$	2	19
Triazine	$C_1^{(5)}$	38	48
Amides	$K_3^{(15)}$	27	4
Benzoic / Phenoxy	$O^{(4)}$	15	5
Sulfonylurea	$B^{(2)}$	11	5
Pyridine	$F_1^{(12)}$	0	6
Other herbicides		8	9
Soybeans		1996	2006
Phosphinic acid	$G^{(9)}$	10	77
Dinitroaniline	$K_1^{(3)}$	20	3
Imidazolinone	$B^{(2)}$	21	2
Sulfonylurea	$B^{(2)}$	9	NA[2]
Diphenyl ether	$E^{(14)}$	8	1
Oxime	$A^{(1)}$	7	1
Aryloxyphenoxy propionic acid	$A^{(1)}$	7	NA
Phenoxy	$O^{(4)}$	5	5
Amides	$K_3^{(15)}$	4	2
Triazine	$C_1^{(5)}$	4	1
Benzothiadiazole	$C_3^{(6)}$	4	NA
Other herbicides		2	6
Cotton		1996	2007
Phosphinic acid	$G^{(9)}$	3	60
Dinitroaniline	$K_1^{(3)}$	26	14
Urea	$C_2^{(7)}$	20	6
Triazine	$C_1^{(5)}$	13	2
Organic arsenical	$Z^{(17)}$	12	1
Benzothiadiazole	$C_3^{(6)}$	3	1
Other herbicides		23	17

Source: Agricultural Resource Management Survey (ARMS), USDA; see website for standard errors of estimates; http://www.ers.usda.gov/Data/ARMS/app/default.aspx?survey=CROP#startForm (last accessed 5/17/11;

1. The capitalized letter is the Herbicide Resistance Action Committee classification for the herbicide family mechanism if action and the superscript number is the Weed Science Society of America classification (Senseman, 2007). B – Acetolactate synthase of acetohydroxy acid synthase inhibitors; C_1 – photosystem II inhibitors; F – carotenoid biosynthesis inhibitors; G – enolpyruvyl shikimate-3-phospate synthase inhibitors; K – mitosis inhibitors; O – synthetic auxins.
2. NA - Estimate does not comply with the USDA disclosure limitation practices, is not available, or is not applicable.

Weed management through cultivation has steadily decreased with the adoption of GM seed for all three crops. It is now less than half of the level in the late 1990s. This is due to the high efficacy of current herbicide-based weed control systems and the increased adoption of reduced tillage systems. While reduced tillage has potential environmental benefits (e.g. reduced fossil fuel use, reduced erosion and attendant water quality problems), increased reliance on herbicide-based control can hasten herbicide resistance. Cultivation adds management diversity to an otherwise herbicide-based weed management system and is a non-selective mechanism for annual weeds. Cultivation for weed control fell from 89% of cotton acres in 1996 to 38% in 2007. Cultivation in corn fell to 15% of acres in 2005. The last reliable estimate of cultivation for weed control in soybeans was 13% in 2002, with more recent rates presumably less.

Table 3. National trends in weed management for corn, soybeans and cotton.

Practice	Corn			Soybeans			Cotton		
	1996	2000	2005	1996	2000	2006	1996	2000	2007
	– (% of total national acres planted on which practice is used) –								
Genetically modified herbicide resistant seed	NA[1]	11	31	7	59	97	NA	58	90
Field scouted for weeds	81	83	89	79	85	91	71	82	92
Burndown herbicide used	9	12	18	33	27	31	6	23	41
Pre-emergence weed control	78	71	61	67	46	28	90	79	73
Post-emergence weed control	59	63	66	78	87	95	62	76	89
Cultivated for weed control	33	38	15	29	17	NA	89	63	38

Source: Agricultural Resource Management Survey (ARMS), USDA).
[1]NA - Estimate does not comply with the USDA-ERS disclosure limitation practices, is not available, or is not applicable.

Pre-emergence herbicide use can provide an indirect measure of diversification of herbicide MOA. MOAs for pre-emergence herbicide usually differ from the MOAs of the post-emergence herbicides that complement GM HR crops. Pre-emergence herbicide use has declined for all crops, with the largest decrease on soybean acreage (Table 3). The implications of other indicators for resistance management are more ambiguous. For example, growers may use a burndown herbicide to plant into a weed-free field. In reduced- or no-till systems, burndown herbicides replace pre-planting tillage to control existing weeds. While weed-free fields may delay resistance, the evolution of resistance might be hastened if growers use the same herbicide for both burndown and post-emergence applications. This multiple use of the same herbicide is likely in GR crops, where glyphosate would be the preferred choice for both types of applications. Burndown herbicide applications remained relatively constant for soybeans, but increased from 9% to 18% of corn acres from 1996-2005 and from 6% to 41% of cotton acres from 1996-2007 (Table 3). Reduced reliance on tillage for weed control, combined with multiple use of the same herbicide for burndown and for post-emergence control works against the diversification of weed management and use of multiple herbicide MOAs.

The resistance management implications of high and increasing rates of field scouting for weeds (Table 3) are also ambiguous. Scouting fields for weeds can be a fundamental approach to delaying evolution of herbicide resistance as it identifies the initial appearance of resistant individuals in time for their elimination before they reproduce. Yet, scouting has little utility in detecting resistance problems unless it is done *following* the herbicide application. The ARMS data do not report whether the scouting is done before applications, after applications, or both. In addition, the increase in weed scouting is associated with a move from preventive weed management – pre-emergence treatments – to a curative approach that relies on post-emergence treatments. Thus, in the later surveys, greater weed scouting could be associated with greater use of post-emergence compounds rather than the combined used of pre- and post-emergence applications relying on different MOAs. This does not appear to be the case, at least for corn and cotton, however. Corn and cotton growers that practice weed scouting appear to apply pre-emergence herbicides on a *higher* percentage of acres, compared to growers that do not scout (Table 4).

Table 4. Use of pre-emergence weed control by method of weed scouting, US national averages

	Corn 2005	Soybeans 2006	Cotton 2007
Weed scouting practiced by:	– % of planted acres using pre-emergence weed control –		
Operator or family member	60	28	76
Employee	77	24[1]	76
Farm supplier or dealer	69	29	80
Independent scout or consultant	65	27	70
Scouting not practiced	56	29	58

Source: USDA, Agricultural Resource Management Survey (ARMS)
1. Estimate not reliable because of large standard error

Table 5 shows the regional variation in the decrease in pre-emergence herbicides use and cultivation for weed control between 1998 and 2007 on cotton acreage. The adoption of GM HR seed and the accompanying post-emergence based weed management program initially gave very high weed control efficacy. This allowed the discontinuation of pre-emergence herbicide and cultivation use, but also reduced the weed management diversity.

The decreased need for cultivation, allowed the adoption of conservation tillage in the Delta, Appalachian, and Southeast regions, where the weed problems had previously limited its use.

Table 5. Regional trends in cotton weed management

Practice	Pacific[1]		Southern Plains		Delta		Appalachian		Southeast	
	1998	2007	1998	2007	1998	2007	1998	2007	1998	2007
	% of total regional acres planted on which practice is used									
GM herbicide resistant seed	NA[2]	97	34	92	24	90	63	84	33	87
Pre-emergence weed control	96	57	90	79	93	62	83	68	85	81
Cultivated for weed control	100	95	67	61	90	11	45	6	66	6

1. Regions: Pacific – Oregon, California, Washington; Southern Plains – Texas, Oklahoma; Delta – Louisiana, Arkansas, Mississippi; Appalachian – West Virginia, Tennessee, North Carolina, Virginia, Kentucky; Southeast – South Carolina, Alabama, Georgia, Florida.
2. NA - Estimate does not comply with the USDA - Economic Research Service disclosure limitation practices, is not available, or is not applicable.

2005/6 Benchmark Study Findings

Another vehicle for assessing the extent of resistance management practices are published results of surveys of grower practices. A series of papers (Shaw et al, 2009, Givens et al, 2009a, Givens et al 2009b) described results of a grower survey conducted in 2005/6 of 1050 producers equally selected from the states of Illinois, Indiana, Iowa, Mississippi, Nebraska, and North Carolina. Selected growers had signed an agreement to use Roundup Ready® (GM, GR) seed. The primary cropping systems practiced on the farms were continuous GR soybean, continuous GR cotton, a GR soybean / GR corn rotation, or GR soybean / non-GR crop rotation. The majority of acreage in Mississippi and North Carolina was in continuous monocropping. Few cotton farmers practiced rotation. Lack of rotation in cotton raises concern about the potential continuous herbicide resistance selection in the fields with GR cotton. The traditional value of crop rotation to manage resistance must be reassessed for HR crops. Whereas the planting date and growth pattern of the crop affect the competitiveness of the weeds that emerge, the weed management program is the primary determinant of weed populations. Over a cycle of repetitions, weed management affects the composition of the weed flora (Webster and Coble, 1997). Weed management is comprised primarily of tillage and herbicides. If an HR crop follows another HR crop, there may be little effect on the herbicide(s) used from year to year and consequently the same herbicide selects the weed population.

Growers planting continuous GR soybeans had been doing so for an average of 4.8 years, while growers who planted continuous GR cotton averaged 5 years. A GR soybean - non-GR crop rotation had been practiced for an average of 6.4 years. Growers responded that glyphosate had replaced non-glyphosate based weed management programs (Givens et al, 2009b). In these cases, glyphosate was at least the foundation, if not the only, herbicide used to manage weeds. Further, while the majority of growers made two or fewer glyphosate applications in a crop, between 30%-40% of the GR cotton growers made three glyphosate applications, depending on farm size. In GR soybeans, 66%-74% of the producers made two of more glyphosate treatments.

Givens et al. (2009b) reported on herbicide use patterns among GR cropping systems. Soybean acres were more likely to receive only glyphosate applications. For example, 85% of those growing continuous GR soybeans applied glyphosate alone, while more than 80% of soybean acres in rotation with corn or a non-GR crop received only glyphosate applications. Cotton acres were most likely to receive herbicides besides glyphosate, with corn acreage intermediate. Continuous GR cotton acres and continuous GR soybean acres were most likely to receive two or more glyphosate applications.

Johnson et al. (2009) reported on grower awareness of resistance and perceptions about different practices to prevent it. Grower awareness and perceptions are significantly related to farm size. Respondents were divided into large (>1,000 acres), medium (500-1,000 acres), and small (<500 acres) categories. While 88% of large and medium growers were aware of weeds' potential to develop resistance, only 75% of small farms were aware. Another way to view these numbers is that one in eight medium and large growers and one in four small growers were unaware of weeds' potential to develop resistance. While about two thirds of large and medium growers had taken actions to prevent resistance, only 43% of small growers reported doing so. Less than a third of growers of any size perceived resistance as a high risk (8-10 on a 10-point scale).

About three quarters of all growers gave "following the label rate" for glyphosate applications "High" rating as an important practice to follow for the prevention of herbicide resistant (8-10 on a 10-pt. scale). In contrast, only about half of growers gave rotating crops, rotating herbicides, using a non-Roundup Ready crop, or tank mixing a high rating. Between 40%-47% of growers (varying by farm size), rated use of tank mixes as high, while fewer than 30% gave tillage a high rating. These results raise the question of whether growers follow the label rate because they think it important to prevent resistance or whether they say that following the label rate is important because it is something that they already practice. Frisvold et al. (2009) found that following the label rate was among the most frequently adopted weed resistance BMPs. A similar issue may arise in the case of tillage. For the most part, growers' ratings varied little between growers practicing no-till, reduced-tillage, or conventional tillage. An exception was the rating of tillage's effectiveness at preventing resistance. Only 17% of no-till producers rated tillage as high, but 32% of reduced-tillage and 38% of conventional tillage growers did so (Johnson et al., 2009).

2006 Syngenta Survey

Foresman and Glasgow (2008) reported on a 2006 study commissioned by Syngenta Crop Protection. The telephone survey collected information from 200 growers in the Corn Belt (North) and 200 from the Cotton Belt (South). Many growers in both the North and South also grew soybeans. More than 90% of growers in both regions used GR seed varieties. The share of total area planted to GR crops was greater among Southern producers (83%) than Northern ones (53%), where more growers planted non-GR corn. Rotating GR with non-GR crops was more prevalent in the North (55% of growers) than the South (20%). In the South, 56% of area was planted consecutively to GR crops in 2005 and 2006. A high percentage of growers made 2-3 glyphosate applications per year (70% in the North 75%; in the South). In the South, only 9% of growers responded that they would rotate out of GR crops in the event of glyphosate resistance.

About half of growers planting corn or cotton applied a pre-emergence herbicide followed by glyphosate. About a third of soybean growers did so. About a fifth of corn, cotton, and southern soybean growers applied glyphosate in tank mixes with other herbicides. A very small percentage of growers used herbicides other than glyphosate. In contrast, significant shares of growers applied only glyphosate, with shares higher among soybean growers. These findings are consistent with those of Givens et al. (2009b) and Frisvold et al (2009) who found evidence that soybean growers were less likely to use multiple herbicides with different MOAs. A significant number of growers used glyphosate only and even larger shares of growers are applying glyphosate 2-3 times per year. Together these suggest significant selection pressure for glyphosate resistance.

2007 Monsanto Survey Findings

Frisvold et al. (2009) reported on a 2007 survey, commissioned by Monsanto, of 1,205 corn, cotton, and soybean producers (at least 400 respondents for each crop). The survey asked growers about use of ten BMPs (Table 6). Growers chose among five responses when asked how frequently they adopted a BMP: (1) always, (2) often, (3) sometimes, (4) rarely, and (5) never. Six BMPs were always practiced by a majority of growers (Table 6). A large share of growers rarely or never practiced three BMPs, however. These included cleaning equipment before moving between fields (53%), using multiple herbicides with different MOAs (28%), and supplemental tillage (53%). Table 6 combines responses for all three producers because adoption patterns were remarkably similar across producer groups. More than 70% of corn, cotton, or soybean growers practiced the same seven BMPs often or always, but all used multiple herbicides with different MOA, cleaned equipment, or practiced supplemental tillage much less frequently. Fewer than half practiced these three BMPs often or always. More corn producers used multiple herbicides with different modes of action often or always (49%) than either cotton (38%) or soybean (28%) growers.

Frisvold et al (2009) also conducted multivariate regression analysis to evaluate the factors that contribute to more or less frequent use of BMPs. They found, with respect to using herbicides with different MOAs, that growers adopted this practice more frequently if they: (a) had more years of education; (b) the more their expected crop yield exceeded the 10-year average yield in their county; (c) they were in a county with reported weed resistance to glyphosate; and (d) also raised livestock. They used multiple herbicides less frequently if they (a) farmed more years

(b) were soybean growers; (c) planted a higher percentage of their targeted crop to GR varieties; and (d) farmed in a county with a higher yield coefficient of variation over the previous 10 years.

Table 6. Frequency of weed resistance BMP adoption among 1205 cotton, corn and soybean growers

BMP	Always	Often	Sometimes	Rarely	Never
		– (% respondents practicing) –			
1. Scout before applying herbicides	57%	26%	11%	3%	2%
2. Scout after applying herbicides	51%	29%	15%	2%	1%
3. Start with clean field	60%	14%	13%	5%	8%
4. Control weeds early	54%	35%	9%	1%	0%
5. Control weeds escapes	45%	34%	15%	4%	2%
6. Clean equipment	15%	11%	20%	22%	31%
7. Use new seed	87%	7%	3%	1%	2%
8. Use multiple herbicides with different MOAs	18%	21%	33%	15%	13%
9. Supplemental tillage	11%	10%	26%	21%	32%
10. Use label rate	74%	19%	4%	1%	0%

Source: Frisvold et al., (2009)

The coefficient of variation (CV) is the standard deviation of yield divided by its mean. It thus serves as a measure of marginal production areas – areas with historically low yields, high yield variability, or both. This variable may also be serving as a proxy for dryland production. Irrigated yields tend to be higher and less variable, leading to a lower CV. Highly variable production outcomes may hinder the observability and trialability of BMPs (Pannell & Zilberman, 2001). With greater yield variability, it may be more difficult for growers to assess outcomes or benefits of BMP adoption. This suggests that counties with high crop yield CVs may be areas to look for low BMP adoption and focus extension programs for resistance management.

Analyzing a sub-sample of the Monsanto study data, Hurley et al. (2009a) found that while more than 65% of corn and cotton growers used a residual herbicide with glyphosate, fewer than 30% of soybean growers did so. About 70% of GR corn and GR cotton growers were planting their GR crop following a GR crop planted the previous year. Nearly half of GR soybean growers were doing so (Hurley et al., 2009a). The survey also asked growers an open-ended question regarding their biggest weed management concerns with no prompting about resistance issues. Weed resistance was a stated concern among 59% of cotton growers, 54% of soybean growers, and 48% of corn growers.

In a related study of the effects of BMPs on weed management costs (also using the Monsanto study data) Hurley et al. (2009b) reported grower planting and herbicide use intentions for 2008 (Table 7). Cotton and soybean growers both planned to plant more than 90% of their crop with GR cultivars, while corn growers planned to plant more than 70% with GR cultivars. Compared to corn and cotton growers, soybean growers planned to treat a smaller share of their GR acres with a residual herbicide. Soybean growers also planned to plant a lower percentage of their GR acres following a GR crop (possibly, because they planned a rotation with non-GR corn).

Table 7. 2008 planned GR crop plantings and residual herbicide use from a survey of 1,205 cotton, corn, and soybean growers.

Variable	Corn	Soybean	Cotton
2008 GR acreage planned (%)	73	96	92
2008 GR acreage with residual planned (%)	66	28	66
2008 GR acreage following GR acreage planned (%)	63	47	68

Source: Hurley et al. (2009b)

Findings from Smaller-Scale Studies

Harrington et al. (2009) conducted an on-line survey of agricultural professionals (growers, researchers, educators, consultants, and administrators) in western and midwestern states about their perceptions of how agricultural biotechnology has affected integrated pest and weed management. Fifty-four responded to survey questions about perceived changes in farming practices resulting from adoption of herbicide resistant (HR) crops (Table 8).

Table 8. Perceived changes in weed management practices resulting from adoption of HR crops from an Internet survey of 54 agricultural professionals.

Weed management practice	Percent of respondents who believed growers were following the practice "less" or "much less" as a result of HR crop adoption
Combination of weed control methods	>60%[1]
Crop rotation for weed control	>40%
Annual rotation of herbicides	>50%
Use of multiple herbicides	>60%
Tillage for weed control	>80%

Source: Harrington et al. (2009)

1. Numbers are derived from a graph in Harrington et al.; exact values were not reported.

Most respondents believed that growers were using a combination of weed control methods, using diverse MOAs, or using tillage less or much less (Table 8). Between 40% and 50% believed growers were using crop rotations less. Among 13 potentia*l*, serious (negative) consequences of widespread HR crop use, respondents rated shifts in weed species composition and development of weed resistance as the first and second most serious. Respondents were asked to rate serious on a scale of 1 (not serious) to 5 (very serious). Shifts in weed composition were rated at 4.04 on average, compared to weed resistance, 3.98. Ratings for other problems ranged from 2.02 to 3.6. Public sector respondents rated weed resistance as more serious (3.96) than private sector respondents did (2.93). The difference was significant at the 1% level.

In a study based on in-depth interviews of 30 Ohio farmers to assess their dominant beliefs about weed introduction, spread, and management strategies, Wilson et al. (2008) found growers attributed weed introduction to factors largely out of their control such as natural factors (wind, wildlife, birds) and poor weed management in neighboring fields. About a quarter of growers emphasized neighbor behavior as a major determinant of weed spread. If growers view weeds and weed resistance as highly mobile and beyond their control, then they will perceive less benefit to undertaking any costly measures to delay resistance. Llewellyn and Allen (2006), in a study of Western Australia, also found that growers believed that herbicide resistant weeds were highly mobile.

In a survey of more than 600 Indiana corn and soybean growers from 2003, Johnson and Gibson (2006) found that only 36% of growers expressed a high level of concern about weed resistance, while 19% expressed low or no concern. On average, only 58% of growers mentioned repeated use of same herbicide MOA as the main factor contributing to weed resistance in an open-ended question about weed resistance. For larger operations (> 2,000 acres), this figure was only 51%.

Summarizing Key Findings

From the mid-1990s to the mid-2000s, there was a pervasive reduction in the diversity of weed control tactics**.** The widespread, complementary adoption of GR cultivars and conservation tillage provided a number of economic and environmental benefits. Yet, it has reduced the diversity of weed management tactics by increasing reliance on purely herbicide-based weed management. From the mid-1990s to the mid-2000s, the share of corn, soybean, and cotton acreage cultivated for weed control fell by 50% or more. There was also a shift away from pre-emergence weed control to post-emergence herbicide use. Post-emergence control often relied on use of glyphosate as the only herbicide and using glyphosate multiple times in a single season. While rotating crops can delay weed resistance, many growers began rotating between GR crops (e.g. GR corn – GR soybean rotations and GR cotton – GR soybean rotations) and the same acres received repeated applications of a single chemistry, glyphosate.

As of the mid-2000s, many growers held attitudes and perceptions one would expect to discourage BMP adoption. A significant share of growers appeared unaware of certain major factors contributing to the evolution of weed resistance as recently as 2005. In results from the Benchmark study, one in eight medium and large growers and one in four small growers were unaware of weeds' potential to develop resistance. Fewer than half of growers rated rotating herbicides or using tank mixes (to diversify exposure to MOAs) as highly effective methods of delaying resistance. Johnson and Gibson (2006) reported that only 58% of growers surveyed mentioned repeated use of the same mechanism of action as a major factor contributing to weed resistance. Many growers may attribute infestation and spread of resistant weeds to factors out of their immediate control such as natural forces (e.g. wind, birds, animals) or poor weed management by their neighbors (Llewellyn and Adams, 2006; Wilson et al., 2008). If growers perceive that preventing weed resistance is beyond their individual control and requires collective grower action, they will have less incentive to take individual actions that incur additional costs to delay resistance. Many growers may also believe that new chemistries or cultivars will soon become available to address resistance problems (Llewellyn et al., 2002; Foresman and Glasgow, 2008). Foresman and Glasgow (2008) reported 92% of respondents were "somewhat" to "very confident" that chemical manufacturers would develop new products to address glyphosate resistance with 3-5 years. Growers have less incentive to conserve the efficacy of an herbicide if they believe substitutes will be available in the future.

In the early, 2000s, the level of concern about weed resistance among many growers was low. Johnson and Gibson (2006) found only 36% of growers expressed a high level of concern about weed resistance, while 19% expressed low or no concern). However, as resistance to glyphosate became more apparent, concern has increased. In a 2007 survey, Hurley et al. reported that resistance was a weed management concern mentioned by 59% of cotton growers, 54% of soybean growers, and 48% of corn growers. More recently, Harrington et al. (2009) reported that agricultural professionals rated weed shifts and resistance as the two most serious concerns. Public sector respondents, however, rated resistance as a more serious concern than did private consultants or growers.

There also appears to be divergence of opinion in the academic community about following label rates. Some studies (e.g. Johnson and Gibson, 2006; Wilson et al., 2008) suggest that making applications below the label rate is a positive part of weed management. While this practice may have some short-term benefits (reduced input costs and herbicides in the environment) it can, under certain conditions, hasten the evolution of resistance. If academics or extension professionals provide growers with mixed messages, the lack of consistency may hinder BMP adoption.

Finally, data on grower resistance concerns and BMP adoption is growing out-of-date. While large amounts of data are available from the mid-2000s (2005-7), resistance problems and awareness have grown significantly since then. The USDA ARMS has collected data on weed management and other production practices for corn, soybeans, and cotton periodically, but with decreasing frequency in recent years. USDA conducted the most recent surveys in 2001 and 2005 for corn, 2002 and 2006 for soybeans, and 2003 and 2007 for cotton. Data from ARMS Phase II surveys for corn and cotton for 2010 are not yet available.

An Economic Model of Weed Resistance Management

Following Llewellyn et al. (2007), adoption of weed resistance BMPs is treated as a dynamic optimization problem. To simplify, time is divided into two periods, the short run (t = 0) and the long run (t = 1). A grower chooses application rates of glyphosate G_t, residual herbicides, r_t and adoption of other BMPs, $\boldsymbol{M}_t$, to maximize the net present value (NPV) of returns over the two periods:

$$(1)\quad NPV = P_0Y_0[1 - \delta_0 (N_0, R_0 , G_0 , r_0 , \boldsymbol{M}_0)] - C_{G0}G_0 - C_{r0}r_0 - C_{M0}(M_0) - V_0 - C_{E0}(G_0 , r_0 , \boldsymbol{M}_0)$$

$$+ \{P_1Y_1[1 - \delta_1 (N_1, R_1 , G_1 , r_1, B_1, \boldsymbol{M}_1)] - C_{G1}G_1 - C_{r1}r_1 - C_{B1}B_1 - \mathrm{C}_{\mathrm{M1}}(M_1) - V_1 - C_{E1}(G_1 , r_1, B_1, \boldsymbol{M}_1)\}\beta$$

with respect to $G_0, G_1, X_0, X_1, B_1, \boldsymbol{M}_0 , \boldsymbol{M}_1$, subject to

$R_1 - R_0 = f(R_0 , G_0, r_0, \boldsymbol{M}_0, X_0)$;

where t subscripts denote time and

P_t = crop price
Y_t = crop yield
δ_t = percent yield loss from weed damage
N_t = pre-treatment weed population
R_t = weed resistance to the herbicide
G_t = level of glyphosate use
r_t = level of residual herbicide use
$\boldsymbol{M}_t$ = vector of resistance management practices
B_1 = level of use of a new "backstop" herbicide that can substitute for glyphosate in the long term
X_0 = behavior of neighbors or external factors that increase resistance
C_{Gt} = constant cost of glyphosate treatments
C_{rt} = constant cost of residual herbicide treatments
C_{Mt} = a cost function for other resistance management practices; $\partial C_{Mt} / \partial \boldsymbol{M}_t > 0$
C_{Et} = a cost function measuring the external environmental costs of weed management practices
C_{B1} = constant cost of backstop herbicide treatments
V_t = other variable costs
β = discount factor; $0 \leq \beta \leq 1$.

In the function δ_t ( ), weed damage increases with the pre-treatment weed population ($\partial\delta_t / \partial N_t > 0$) and with the level of resistance to glyphosate ($\partial\delta_t / \partial R_t > 0$). Use of glyphosate and residual herbicides reduces damage ($\partial\delta_t / \partial G_t < 0$; $\partial\delta_t / \partial r_t < 0$). Other BMPs, such as supplemental tillage, starting with a clean field, or cleaning equipment could also reduce damage ($\partial\delta_t / \partial \boldsymbol{M}_t < 0$). Resistance limits the ability of glyphosate to control damage ($\partial^2\delta_t / \partial G_t \partial R_t > 0$). In the function f ( ) that characterizes the evolution of resistance to glyphosate, use of residual herbicides with different mechanisms of action slows resistance ($\partial R_1 / \partial r_0 < 0$) as will use of other BMPs ($\partial R_1 / \partial \boldsymbol{M}_0 < 0$). Use of glyphosate, in contrast, speeds resistance ($\partial R_1 / \partial G_0 > 0$).

This stylized model captures a number of important aspects of weed resistance management. GR seed varieties increased the short-run profitability of increasing glyphosate use relative to other strategies for weed control such as tillage (a component of $\boldsymbol{M}_0$) or use of pre-emergence herbicides (r_0). If the short-run effect were strong enough, one would expect to see a sharp increase in glyphosate use accompanied by a decrease in pre-emergence herbicide use and in tillage. As the various empirical sources discussed above show, this has already occurred. Use of herbicides with different MOAs from glyphosate (another component of $\boldsymbol{M}_0$) may be less profitable than simply using glyphosate in the short-run. Increased use of glyphosate in the short-run, however, increases the level of long-run resistance, R_1, weed damage δ_1, and weed control costs. Thus, over-reliance on glyphosate can reduce long-run profitability. BMPs that reduce short-run weed damage, δ_0, are more likely to be adopted than those that only slow resistance. Growers may have little short-run incentive to use residual herbicides, r_0, if they achieve effective, low-cost control with glyphosate.

Equation (2) captures how grower perceptions can influence resistance management. First, if growers are unaware of how their short-run practices contribute to resistance they may ignore equation (2), instead choosing to maximize only short-run returns. Second, growers may not be aware of the most effect practices they may adopt to delay resistance (i.e. they may be somewhat aware of some general relationships in equation (2), but be mistaken about the relative contribution of different actions). Third, they may attribute the development of resistance to external factors, X_0, such as natural forces or the behavior of their neighbors. If growers believe the effects of external forces on resistance are much greater than the effects of their own actions (i.e. $|\partial R_1 / \partial X_0 > 0)|$ is much greater than combined effects of $|\partial R_1 / \partial r_0 < 0)|$, $|\partial R_1 / \partial \boldsymbol{M}_0 < 0|$, and $|\partial R_1 / \partial G_0 > 0|$), they may foresee little incentive to manage resistance on their own fields. Fourth, if growers believe a new backstop herbicide will become available in the future with comparable cost and weed control properties as glyphosate, (i.e. $\partial\delta_1 / \partial B_1 < 0$ is equivalent to $\partial\delta_0 / \partial G_0 < 0$ and C_{B1} equivalent to C_{G0}), they will have little incentive to reduce short-run profits in order to slow resistance.

One can characterize three cases describing economic incentives for BMP adoption. In the first, BMPs have both short-run and long-run benefits. If growers are aware of this, adoption rates will be high and little public intervention may be needed. This explains why some BMPs already have high adoption rates. If growers are unaware or uncertain that they can achieve similar short-run returns with BMPs, extension may play a role in demonstrating the similarity in returns. In this case, studies such as Weirich, et al. (2011) may be especially important.

In the second case, BMPs (including use of residual herbicides) have net costs in short-run, but net benefits that producers can capture in the long term. For growers, the short-run costs of this year's weed management program are relatively certain, while long-term benefits of resistance management are uncertain. In the economic model above, uncertainty about the future can act like a reduction in discount factor, β. Growers literally discount potential long-run returns relative to short-run returns. Again, extension and grower education programs can play a positive role by reducing uncertainty and explaining inter-temporal trade-offs. Growers may also discount the value of resistance management if they expect industry to develop new chemistries with comparable cost and effectiveness as current herbicides. To date, chemical companies have met this expectation as herbicide prices have risen more slowly than prices of other inputs (Frisvold and Reeves, 2010). However, no herbicides with new mechanisms of action have been registered in the United States since 1993. Another role of extension and education programs may be to encourage growers to consider a future when new compounds do not become available and they will need to conserve the efficacy of the ones they have.

Although Monsanto's patent for glyphosate has expired, they still derive substantial revenue from sales of glyphosate and GR seed varieties. The economic model can be used to characterize their recent practice of subsidizing purchases of residual herbicides, even those sold by other companies. Paying subsidies in time $t = 0$ can increase residual herbicide use (r_0 increases). Weighed against the subsidy cost, however, are increased sales of glyphosate in the future ($C_{G1}G_1$) and future sales of GR seed (part of V_1). Subsidizing sales of residual makes sense from this long-term perspective.

In a third case, BMPs (including use of residual herbicides) have net costs in short-run, while long-term benefits are difficult for individual growers to capture. The effectiveness of an herbicide is a "common pool resource." If resistant weeds are mobile enough, individual action may be insufficient to delay resistance. Here, effectiveness of resistance management depends on grower collective action, but there may be "free riding." The optimal strategy overall may be for all growers to practice resistant management. However, an individual grower would have the highest benefit if everyone else complied with resistance management (and incurred costs of compliance), while he does not. The problem here is that if many growers adopt this strategy, then resistance is not effectively delayed. In this case, there may be a role for public policies. Intervention need not follow a top-down, regulatory approach (e.g. mandating or prohibiting practices or compounds). Rather, it could take a form similar to grower-led pest eradication programs. Growers could agree upon necessarily resistance management measures, collectively. The role of government agencies would be to provide supporting information and resources and to enforce the growers' collective decisions and prevent free riding.

A related problem can arise because growers cannot capture full social benefits of weed management practices that have fewer negative environmental impacts. Glyphosate-based systems combined with conservation tillage provide a number of environmental benefits compared to earlier weed management systems (see Frisvold and Reeves (2010) for more extensive references). For example, glyphosate substitutes for herbicides with higher toxicity and persistence in the environment, while GR crops encourage conservation tillage, which in turn can reduce soil erosion, attendant water pollution, and fossil fuel use. Society has an interest in preventing a return to environmental problems associated with tillage or greater reliance on more toxic and persistent herbicides. Growers, however, do not capture these long-term benefits and thus have less economic incentive to adopt costly BMPs on their own. In the context of the economic model, although the environmental costs of weed management, C_{Et}, are a real cost to society, growers may ignore these costs when maximizing farm profits. USDA's Environmental Quality Incentives Program (EQIP) provides cost-sharing payments for conservation practices. One future policy option might to expand payment eligibility to include practices that conserve pest susceptibility over the longer term.

Conclusions

Diverse data sources from the mid-1990s to mid-2000s document the reduced diversity of weed management practices and increased selection pressure contributing to the evolution of weeds resistant to glyphosate. While much of the data documents adoption of GR crops and development of GR weeds, the general problems of resistance management apply to other compounds as well. Several studies document which BMPs are being adopted and which ones are not. One key finding is that adoption levels vary more across the type of practice than the type of crop. For resistance management to be effective more research is needed to identify how adopters differ from non-adopters and which economic factors pose barriers to BMP adoption.

References

Beckie, H.J. (2006). Herbicide-resistant weeds: Management tactics and practices. Weed Tech. 20:793-814.

Burgos, N., S. Culpepper, P. Dotray, J.A, Kendig, J, Wilcut, and R.L. Nichols. R. 2006. Managing herbicide resistance in cotton cropping systems. Carey, NC: Cotton Incorporated.

Foresman, C and L.Glasgow. 2008. Grower perceptions and experiences with glyphosate resistant weeds. Pest Manag. Sci. 64:388–391.

Frisvold, G.B., T.M. Hurley, and P.D. Mitchell. 2009. Adoption of best management practices to control weed resistance by corn, cotton and soybean growers. AgBioForum 12:370-381.

Frisvold, G.B. and J.M. Reeves. 2010. Resistance management and sustainable use of agricultural biotechnology. AgBioForum 13:343-359.

Givens, W.A., D.R. Shaw, G.R. Krueger, W.G. Johnson, S.C. Weller, B.G. Young, R.G. Wilson, M.D.K. Owen and D. Jordan. 2009a. Survey of tillage trends following the adoption of glyphosate-resistant crops. Weed Tech. 23:150-155.

Givens, W.A., D.R. Shaw, W.G. Johnson, S.C. Weller, B.G. Young, R.G. Wilson, M.D.K. Owen, D. Jordan. 2009b. A grower survey of herbicide use patterns in glyphosate-resistant cropping systems. Weed Tech. 23:156-161.

Harrington, J., Byrne, P.F., Peairs, F.B., Nissen, S.J., Westra, P., et al. 2009. Perceived consequences of herbicide-tolerant and insect-resistant crops on integrated pest management strategies in the western United States: Results of an online survey. AgBioForum 12:412-421.

Holt, J.S., and H.M. Lebaron. 1990. Significance and distribution of herbicide resistance. Weed Tech. 4: 141-149.

Hurley, T.M., P.D. Mitchell, and G.B. Frisvold. 2009a. Effects of weed resistance concerns and resistance management practices on the value of Roundup Ready® crops. AgBioForum 12:291-302.

Hurley, T.M., P.D. Mitchell, and G.B. Frisvold. 2009b. Weed management costs, weed best management practices, and the Roundup Ready® weed management program. AgBioForum 12:281-290.

Johnson, W.G. and K.D. Gibson. 2006. Glyphosate-resistant weeds and resistance management strategies: An Indiana grower perspective. Weed Tech. 20:768-772.

Johnson, W.G., M.D.K. Owen, G.R. Kruger, B.G. Young, D.R. Shaw, R.G. Wilson, J.W. Wilcut, D.L. Jordan, and S.C. Weller. 2009. U.S. farmer awareness of glyphosate-resistant weeds and resistance management strategies. Weed Tech. 23:308-312. 2009.

Llewellyn, R.S. and D.M. Allen. 2006. Expected mobility of herbicide resistance via weed seeds and pollen in a Western Australian cropping region. Crop Protection 25:520-526.

Llewellyn, R.S., R.K. Lindner, D.J. Pannell, S.B. Powles. 2002. Resistance and the herbicide resource: perceptions of Western Australian grain growers. Crop Protection 21:1067-1075.

Llewellyn, R.S., R.K. Lindner, D.J. Pannell, S.B. Powles. 2007. Herbicide resistance and the adoption of integrated weed management by Western Australian grain growers. Agric. Econ. 36:123-130.

Pannell, D.J., and D. Zilberman. 2001. Economic and sociological factors affecting growers' decision making on herbicide resistance. In S. Powles and D. Shaner (Eds.), Herbicide Resistance and World Grains Boca Raton: CRC Press, pp. 252-277.

Powles, S.B., and D.L. Shaner (eds.). 2001. Herbicide resistance and world grains. Boca Raton, FL: CRC Press.

Senseman, S. A. Herbicide Handbook, 2007. 9th ed.; Weed Science Society of America: Lawrence, KS.

Shaw D.R., W.A. Givens, L.A. Farno, P.D. Gerard, D. Jordan, W.G. Johnson, S.C. Weller, B.G. Young, R. G. Wilson and M.D K. Owen. 2009. Using a grower survey to assess the benefits and challenges of glyphosate-resistant cropping systems for weed management in U.S. corn, cotton, and soybean. Weed Tech. 23:134-149.

Shaner, D.L. (1995). Herbicide resistance: Where are we? How did we get here? Where are we going? Weed Technology, 9, 850-856.

Shaw, D.R., M.D.K. Owen, P.M. Dixon, S.C. Weller, B.G. Young, R.G. Wilson, and D.L. Jordan. 2011. Benchmark study on glyphosate-resistant cropping systems in the United States. Part 1: Introduction to 2006-2008. Pest. Manag. Sci. 67:741-746.

Webster, T.M. and H.D. Coble. 1997. Changes in the weed species composition of the southern United States: 1974 to 1995. Weed Tech. 11:308-317.

Weirich, J.W., D.R. Shaw, M.D.K. Owen, P.M. Dixon, S.C. Weller, B.G. Young, R.G. Wilson, D.L. Jordan. 2011. Benchmark study on glyphosate-resistant cropping systems in the United States. Part 5: Effects of glyphosate-based weed management programs on farm-level profitability. Pest. Manag. Sci. 67:781-784.

Wilson, R.S., M.A. Tucker, N.H. Hooker, J.T. LeJeune and D. Doohan. 2008. Perceptions and Beliefs about Weed Management: Perspectives of Ohio Grain and Produce Farmers. Weed Tech. 22:339-350.

Wilson, R.G., B.G. Young, J.L. Mathews, S.C. Weller, W.G. Johnson, D.L. Jordan, M.D.K. Owen, P.M. Dixon, and D.R. Shaw. 2011. Benchmark study on glyphosate-resistant cropping systems in the United States. Part 4: weed populations and soils seedbanks. Pest. Manag. Sci. 67:771-780.