Weed Technology 2016 30:1–12

Differences in Glyphosate-Resistant Weed Management Practices over Time and Regions

Xia "Vivian" Zhou, Roland K. Roberts, James A. Larson, Dayton M. Lambert, Burton C. English, Ashok K. Mishra, Lawrence L. Falconer, Robert J. Hogan, Jr., Jason L. Johnson, and Jeanne M. Reeves*

The objective of this research was to describe proportional differences across time and region in management practices among southern cotton farmers who experienced glyphosate-resistant (GR) weeds on their farms earlier than those who experienced them later and among farmers who were closest to one of four historical outbreak epicenters: Lauderdale County, TN; Macon County, GA; Edgecombe County, NC; and Terry County, TX. A mail survey was conducted with cotton farmers in 2012 from 13 southern, cotton-producing states. Survey responses on practices used by farmers were classified into three broad categories of labor, mechanical/tillage/chemical (MTC), and cultural. Proportions of respondents using practices from each category were identified by time and region; across which, proportional-difference tests were conducted. Results indicated respondents encountering GR weeds earlier were more likely than farmers who experienced them later to use the three broad-category practices (labor, 98 vs. 92%; MTC, 95 vs. 89%; and cultural, 86 vs. 76%) and specific practices, including hooded sprayers (76 vs. 58%), in-season herbicide change (83 vs. 60%), and field-border management (60 vs. 35%). Also, respondents closest to Lauderdale County were more likely than farmers closest to Edgecombe County to use broad-labor practices (99 vs. 91%) and specific practices, including hand hoeing (96 vs. 84%), hand spraying (49 vs. 31%), spot spraying (76 vs. 59%), wick applicator (13 vs. 11%), and field-border management (58 vs. 39%). Education programs on weed management can be developed and tailored according to the time and regional differences to provide effective information and communication channels to farmers.
Nomenclature: Cotton, *Gossypium hirsutum* L.
Key words: Glyphosate, management practices, weed resistance.

El objetivo de esta investigación fue describir las diferencias proporcionales entre productores sureños de algodón en el uso de prácticas culturales, considerando el momento y la región, para productores que han tenido malezas resistentes a glyphosate (GR) en sus fincas primero y productores que las han tenido después, y entre productores que estuvieron cerca de uno de cuatro epicentros históricos de aparición de resistencia: condado Lauderdale, Tennessee; condado Macon, Georgia; condado Edgecombe, North Carolina; y condado Terry, Texas. Se realizó una encuesta por correo con productores de algodón en 2012 en 13 estados sureños productores de algodón. Las respuestas de la encuesta sobre las prácticas usadas por los productores fueron clasificadas en tres amplias categorías: mano de obra, mecánicas/labranza/químicas (MTC), y culturales. Las proporciones de los que respondieron que usaron prácticas de cada categoría fueron identificadas por momento y región; entre las cuales se realizaron pruebas de diferencias entre proporciones. Los resultados indicaron que quienes respondieron y encontraron malezas GR temprano, tuvieron más probabilidad de usar las tres categorías de prácticas que aquellos que encontraron malezas GR después (labranza, 98 vs. 92%, MTC, 95 vs. 89%, y cultural, 86 vs. 76%) y prácticas específicas que incluyeron aspersores con coberturas de campana (76 s. 58%), cambio de herbicidas durante la temporada de producción (83 vs. 60%), y el manejo de malezas en los bordes de los campos (60 vs. 35%). Además, los encuestados más cercanos al condado Lauderdale fueron los que tuvieron una mayor probabilidad de usar prácticas con mano de obra (99 vs. 91%) que los productores cercanos al condado Edgecombe, y prácticas que incluyeron labranza manual con azadón (96 vs. 84%), aplicación de herbicidas manual (49 vs. 31%), aplicaciones dirigidas (76 vs. 59%), aplicador con azadón químico (13 vs. 11%), y manejo de malezas en los bordes del terreno (58 vs. 39%). Los programas de educación en el manejo de malezas pueden ser desarrollados y dirigidos dependiendo de las diferencias en los momentos y las regiones en que se detecta la resistencia para brindar información y canales de comunicación efectivos para los productores.

DOI: 10.1614/WT-D-15-00056.1
* Research Associate, Professor, Professor, Associate Professor, and Professor, Department of Agricultural and Resource Economics, University of Tennessee, Knoxville, TN 37996; Professor, Department of Agricultural Economics and Agribusiness, Louisiana State University, Baton Rouge, LA 70803; Extension Agricultural Economist, Delta Research and Extension Center, Mississippi State University, Stoneville, MS 38776; Assistant Professor and Associate Professor, Department of Agricultural Economics, Texas A&M University, Stephenville, TX 76401; Director, Agricultural and Environmental Research, Cotton Incorporated, Cary, NC 27513. Corresponding author's E-mail: xzhou11@utk.edu

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

The adoption of herbicide-resistant crops has increased dramatically (Bonny 2008; Duke and Powles 2008; Owen and Zelaya 2005). Glyphosate is a POST herbicide used to control more than 300 types of weeds, including herbaceous, sedge, broadleaf, and woody weeds (Green 2007). By 1996, glyphosate was used to control 74 of the 76 world's persistent weeds (Franz et al. 1996; Holm et al. 1977 [cited by Green 2007]). Most herbicide-resistant crops were glyphosate-resistant (GR), including soybean [*Glycine max* (L.) Merr.] introduced in 1996, cotton in 1997, and corn (*Zea mays* L.) in 1998 (Kruger et al. 2009). Within 6 yr after commercialization, farmers in the United States had adopted GR soybean on 80% of soybean area (Green 2012). Adoption reached 80% of planted area 8 and 10 yr after GR cotton and corn were introduced, respectively (Green 2012). Widespread adoption of GR crops occurred because of reduced labor input, and production cost because of glyphosate replacing more-costly weed-specific and persistent herbicides and higher yields and profitability because of more-efficient and simpler weed management. The introduction of GR crops encouraged no-tillage and conservation tillage because glyphosate could be sprayed over the top of growing crops to control weeds (Roberts et al. 2006).

Glyphosate was effective in controlling weeds, easy to apply on growing crops, and relatively inexpensive, so many producers applied it multiple times a year after adopting GR crops. Recurrent application of this highly effective herbicide led to high selection pressure and was a primary factor for promoting the development of GR weeds (Beckie 2006; Frisvold et al. 2009). Thus, the overuse of glyphosate on GR crops led to, inter alia, GR Palmer amaranth (*Amaranthus palmeri* S. Wats), horseweed [*Conyza canadensis* (L.) Cronq.], and common ragweed (*Ambrosia artemisiifolia* L.). Herbicide-resistant weeds can increase weed control and other production costs, reduce crop yields, and even decrease land value (Anonymous 2002; Brandon 2011; Rowland et al. 1999). Because herbicide options to control GR weeds were limited, farmers began to control the weeds with tillage, hand hoeing, and other labor-intensive practices; use of non-GR crops; and returned to older residual herbicides and sprayer technologies (Baldwin 2011; Frisvold et al. 2009; Johnson et al. 2009b; Robinson 2010).

Cotton growers have experienced more problems with weed resistance because of cotton's slower emergence after planting and fewer registered herbicides compared with other major row crops (Laws 2010; Norsworthy et al. 2008). The first documented cases of GR Palmer amaranth in cotton occurred in 2000 in Lauderdale County, TN (Hayes et al. 2002; Steckel 2006), and in 2003 in Edgecombe County, NC (Yancy 2003). The first confirmed case of GR Palmer amaranth in cotton occurred in 2005 (Culpepper et al. 2006) in Macon County, GA. GR Palmer amaranth and horseweed have since been confirmed in Alabama, Arkansas, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia (Culpepper et al. 2008; Duzy et al. 2011; Heap 2008; Johnson et al. 2009a; Roberson 2011; VanGessel 2001). In 2012, GR Palmer amaranth was confirmed in cotton in Terry County, TX (Cline 2013).

The rapid spread of GR weeds calls for the development of appropriate and effective management techniques to control them (Harrington et al. 2009; Owen and Zelaya 2005). Learning about weed management practices used by farmers is the first step toward providing guidance in designing appropriate strategies. Previous survey research about GR weeds has focused primarily on farmer awareness and perceptions about the problem and on farmer use of selected weed-control practices (Foresman and Glasgow 2008; Givens et al. 2011; Johnson et al. 2009b; Llewellyn et al. 2002; Prince et al. 2012; Zhou et al. 2015). Most farmers are acutely aware of the potential for weeds to develop resistance to herbicides, and growers in the southern United States are more-frequently reported as having GR weeds on their farms (Foresman and Glasgow 2008; Givens et al. 2011; Johnson et al. 2009b; Llewellyn et al. 2002; Prince et al. 2012). Prior survey research indicates that farmers have relied on an assortment of chemical and cultural practices to manage resistant weeds on their farms, and no regional differences in management practices were found among the east, west, and south regions of the United States (Foresman and Glasgow 2008; Frisvold et al. 2009; Givens et al. 2011; Johnson et al. 2009b; Prince et al. 2012). Although farmers in the southern United States reported GR weeds as a serious issue more frequently than did farmers in other regions of the United States

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

Table 1. Numbers and distribution of respondents who provided the year in which glyphosate-resistant weeds were first identified on their farms by year.

Year	Respondents	Distribution	
	No.	%	cumulative %
1995	1	1	
1999	2	1	2
2000	7	4	5
2001	1	1	6
2002	4	2	8
2003	6	3	11
2004	12	7	18
2005	8	4	22
2006	21	11	34
2007	22	12	46
Weed-A[a]	84		
2008	34	18	64
2009	38	21	85
2010	19	10	95
2011	9	5	100
Weed-B[a]	100		
Total	184		

[a] Respondents were separated into two groups using the inflection year (2008) for the cumulative distribution of respondents (Figure 2) as the separator. Respondents who first identified weed resistance on their farms before the inflection year (2007 or earlier) comprised group Weed-A. Respondents who first identified resistance in 2008 or later constituted group Weed-B.

(Prince et al. 2012), little research has been conducted on describing and comparing GR weed-management systems across the years or regions within the southern United States. The objectives of this study were to describe and compare differences in management practices used by southern cotton farmers (1) who identified GR weeds on their farms earlier than those who identified GR weeds on their farms later (Table 1), and (2) who identified GR weeds on their farms in the regions closest to each of the four outbreak epicenters: Lauderdale County, TN; Macon County, GA; Edgecombe County, NC; and Terry County, TX.

Materials and Methods

Population and Sampling Size. A mail survey of cotton farmers was conducted in 2012 to obtain data about farmer experiences with, and adaptations to, herbicide-resistant weeds. The population of interest was the set of active cotton producers in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, Missouri, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia. The list frame of 13,894 cotton producers for the 2010 marketing year was furnished by the Cotton Board in Memphis, TN (J. Reeves, personal communication). A random sample of 2,500 cotton farmers (17.9% of the list frame), which corresponds to a 99% confidence interval with a 2% margin of error (Lohr 1999, pp. 39–42) was selected from the list frame to receive the survey.

Sampling Strategy. The sample was weighted geographically in relation to the documented cases of weed resistance in three historical outbreak epicenters of Lauderdale County, TN (Lauderdale region); Edgecombe County, NC (Edgecombe region); and Macon County, GA (Macon region) (Figure 1). The epicenter within each geographic cluster of population counties (Figure 1) was the county in which the earliest case of GR weeds in cotton was reported in that cluster. A cluster-based sampling strategy was used as the survey sampling design, whereby counties were considered primary sampling units. Counties and cotton farmers in a county were jointly and randomly selected, using the Tillé (1996) method, an unequal probability sampling without replacement algorithm. The probability sampling weights assigned to each county were based on three criteria: (1) the proportion of cotton acres in that county to the total cotton acres in the 13-state region in 2010 (USDA-NASS 2011); (2) the straight-line distance of the most-dense cotton-growing area in a county to the closest one of the three epicenters; and (3) the number of cotton producers in each county. This sampling strategy increased the likelihood that cotton-producing counties that were located closer to the nearest epicenter and had more cotton acres or producers were more likely to be selected (Zhou et al. 2015). Figure 1 highlights the spatial distribution of the selection weights. Darker shaded counties have larger weights.

Survey Planning and Development. Following the Dillman (1978) mail survey design, a postcard was first mailed to each randomly selected cotton producer to inform him or her of the survey questionnaire coming in a week. The initial survey mailing, including the questionnaire, a postage-paid return envelope, and a cover letter, was sent on

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

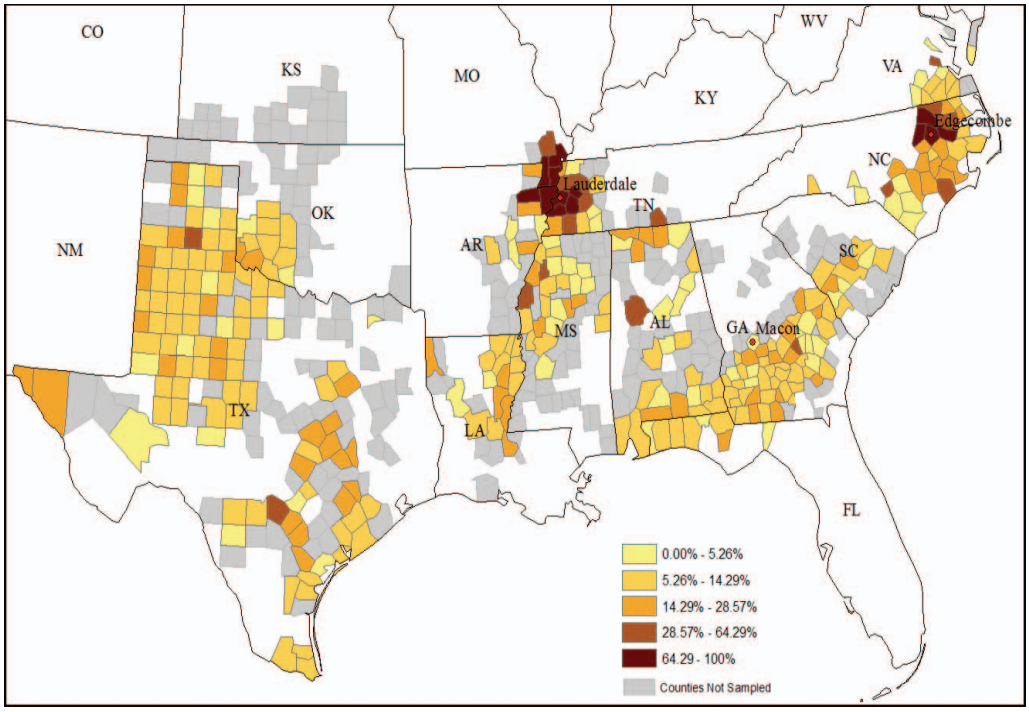


Figure 1. Sampled counties in 13 cotton-producing states for 2012 weed-resistance survey. The probabilities of farmers within the selected counties receiving the survey questionnaire were based on three criteria: (1) the proportion of cotton acres in the county compared with the total cotton acres in the 13-state region in 2010 (USDA NASS 2011), (2) the straight-line distance of the most-dense cotton-growing area in the county to the closest of the three original outbreak epicenters in which weed resistance was initially documented (Lauderdale County, TN; Macon County, GA; Edgecombe County, NC), and (3) the number of cotton producers in each county. This sampling strategy ensured that counties with relatively more cotton production were more likely to be selected, but the likelihood of selection was discounted by their distance from the three original outbreak epicenters. (Color for this figure is available in the online version of this article.)

February 15, 2012, and a reminder postcard was mailed 1 wk later. A follow-up mailing, including the cover letter, questionnaire, and postage-paid return envelope was mailed on March 7, 2012, to cotton producers who did not respond to previous inquiries. Finally, the third postcard was mailed as a reminder on March 15, 2012 (Zhou et al. 2015).

Questionnaire Development. Farmers were asked to identify all herbicide-resistant weed species on their farms, the herbicide to which the weed was resistant, the crops for which the weed was a problem, the number of acres on which the weed was a problem, and the year when the herbicide-resistant weed was first identified. The survey asked farmers about practices they used to control resistant weeds on their farms. Those practices included (1) tillage practices (e.g., no-tillage, conservation tillage, conventional tillage) before and after they identified resistant weeds on their farms; (2) herbicide-resistant crops planted on their farms (Liberty Link [Bayer CropScience, Research Triangle Park, RTP, NC 27709], Widestrike [Dow AgroSciences, 9330 Zionsville Road, Indianapolis, IN 46268], and Roundup Ready/Flex [Monsanto Company, 800 N. Lindburgh Blvd., St. Louis, MO 63167]) before and after resistant weed problems were identified; and (3) other practices they used to manage weed resistance on their farms (Tables 2 and 3). The weed-control practices identified in the survey were broadly categorized as *labor*, *mechanical/tillage/chemical* (*MTC*), and *cultural*, with each category containing several specific practices (Tables 2 and 3). A respondent was included in one or more of the broad weed-control categories if he or she reported using at least one of the specific practices in that category. The survey also asked farmers to rate the effectiveness of the weed-control practices they used.

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

Table 2. Management practices used to control glyphosate-resistant weeds across years.

Category	1995–2007 (Weed-A)		2008–2011 (Weed-B)	
	No.	%[a]	No.	%[b]
Labor[c]	82	98**	92	92**
Field scouting	52	62	50	50
Hand hoeing	78	93	87	87
Cleaning harvest equipment	39	46	48	48
Global positioning system weed mapping	0	0	1	1
Hand spraying to spot-spraying weeds	38	45	36	36
Collaborating with neighbors	6	7	9	9
Other	1	1	2	2
Mechanical/tillage/chemical[d]	80	95*	89	89*
Increased conventional tillage	10	12	13	13
Fall residual herbicide program	11	13	12	12
Variable rate spray technology	7	8	10	10
Summer fallowed fields	3	4	2	2
Hooded sprayer to spot-spray weeds	64	76**	58	58**
Fall tillage after harvest to kill weeds	22	26	16	16
Change in-season herbicide program/chemistry	70	83***	60	60***
Wick applicator/weed wiper	20	24	16	16
Other	5	6	7	7
Cultural[e]	72	86*	76	76*
Different herbicide-resistant crop[f]	12	14	8	8
Abandoned part or all of a crop in a field	5	6	5	5
Winter cover crop to suppress weeds	33	39	36	36
Narrow row spacing	8	10	5	5
More crop rotations	34	40	27	27
Controlled weeds in field boarders/ditches	50	60***	35	35***
Burned field stubble/boarders/ditches	5	6	3	3
High plant population	4	5	2	2
Other	1	1	1	1

[a] The denominator for the percentage is 84, which is the number of respondents who first identified glyphosate-resistant weeds on their farms in 2007 or earlier (Table 1).

[b] The denominator for the percentage is 100, which is the number of respondents who first identified glyphosate-resistant weeds on their farms in 2008 or later (Table 1).

[c] Number of respondents who used at least one practice in the broad labor category.

[d] Number of respondents who used at least one practice in the broad mechanical/tillage/chemical category.

[e] Number of respondents who used at least one practice in the broad cultural category.

[f] Number of farmers who used other herbicide-resistant crops (Liberty Link, Widestrike, and Roundup Ready/Flex).

* Significant at 0.10; ** significant at 0.05; *** significant at 0.01.

Survey Respondent Groups. To address the first objective of this study, Table 1 presents the numbers of respondents who provided the year when they first identified GR weeds on their farms, from 1995 to 2011. The respondents were separated into two groups using the inflection year (2008) for the cumulative distribution of respondents (Figure 2) as the separator. Respondents who first identified weed resistance on their farms before the inflection year (in 2007 or earlier) comprised group *Weed-A*. Respondents who first identified resistance in 2008 or later constituted group *Weed-B*. Frequencies of weed-control practices and percentages of respondents using the practices are reported by group in Table 2.

Data Analysis. Sample proportion tests were performed between groups Weed-A and Weed-B to test for statistical differences in the proportions of respondents using each broad weed-management category and using each weed-control practice (Snedecor and Cochran 1967). The null hypothesis for a particular category was H_0: $m_b = m_a$, where m_b and m_a are the proportions of respondents using each category or practice from Weed-B and Weed-A, respectively. To test the proportion difference, a z-score statistic was calculated as $z = (m_b - m_a)/SE$, where $SE = \{m(1 - m)[(1/n_b) + (1/n_a)]\}^{0.5}$, the standard error; $m = (m_b n_b + m_a n_a)/(n_b + n_a)$; and n_b and n_a represent the numbers of respondents in Weed-B and Weed-A, respectively, who reported using the particular category or practice.

Similarly, sample proportion tests were used to test for statistical difference in the proportions of farmers in the Lauderdale, Macon, and Edgecombe regions (Figure 3) using each broad category and each practice (Snedecor and Cochran 1967). In addition to the three epicenters, Terry County, TX (Terry region), was added as a new epicenter for respondent counties in Texas and Oklahoma to differentiate that region from the Lauderdale region. The Terry region was added because the GR-weed problems identified by respondents from that region had not yet been acknowledged in the literature before the survey was conducted in 2012 (Cline 2013). Frequencies of weed-control practices and percentages of respondents using the practices are reported by region in Table 3. Spearman rank-order correlation coefficients were estimated using STATA Release 13 software (StataCorp 2013; Stata-

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

Table 3. Management practices used to control glyphosate-resistant weeds for respondents close to the four epicenters.[a]

Categories	Lauderdale, TN		Macon, GA		Edgecombe, NC		Terry, TX	
	No.	%[b,c]	No.	%[b,d]	No.	%[b,e]	No.	%[b,f]
Labor[g]	70	99 a	36	95	64	91 b	6	75
Field scouting	35	49 b	14	37 b	49	70 a	5	63
Hand hoeing	68	96 a	34	89	59	84 b	6	75
Cleaning harvest equipment	30	42	22	58	33	47	3	38
Global positioning system weed mapping	n/a	n/a	n/a	n/a	1	1	n/a	n/a
Hand sprayer to spot-spray weeds	35	49 a	14	37	22	31 b	3	38
Collaborate with neighbors	8	11	1	3	6	9	n/a	n/a
Others	1	1	n/a	n/a	2	3	n/a	n/a
Mechanical/tillage/chemical[h]	65	92	36	95	64	91	6	75
Increased conventional tillage	11	15	5	13	6	9	1	13
Fall residual herbicide program	13	18	5	13	3	4	2	25
Variable rate spray technology	3	4	4	11	8	11	2	25
Summer fallowed fields	2	3	1	3	n/a	n/a	2	25
Hooded sprayer to spot-spray weeds	54	76 a	27	71	41	59 b	1	13
Fall tillage after harvest to kill weeds	22	31	7	18	8	11	3	38
Changed in-season herbicide program/chemistry	50	70	26	68	52	74	3	38
Wick applicator/weed wiper	9	13 b	19	50 a	8	11 b	n/a	n/a
Others	3	4	1	3	7	10	1	13
Cultural[i]	55	77	32	84	57	81	6	75
Other herbicide resistant crops[j]	7	10	5	13	8	11	1	13
Abandoned part or all of a crop in a field	3	4	3	8	3	4	1	13
Winter cover crop to suppress weeds	17	24 b	15	39	37	53 a	n/a	n/a
Narrow row spacing	7	10	2	5	4	6	n/a	n/a
More crop rotations	27	38	14	37	17	24	4	50
Controlled weeds in field boarders/ditches	41	58 a	17	45	27	39 b	2	25
Burned field stubble/boarders/ditches	8	11	1	3	n/a	n/a	n/a	n/a
High plant population	3	4	3	8	n/a	n/a	n/a	n/a
Others	1	1	n/a	n/a	1	1	n/a	n/a

[a] Abbreviation: n/a, not available.

[b] Proportions with different letters within a row are different at the 0.10 significance level; the same letter or no letter indicates no significant difference in proportions.

[c] The denominator for the percentage is 71, which is the number of respondents who identified glyphosate-resistant weeds on their farms close to the Lauderdale, TN. epicenter.

[d] The denominator for the percentage is 38, which is the number of respondents who identified glyphosate-resistant weeds on their farms close to the Macon, GA epicenter.

[e] The denominator for the percentage is 70, which is the number of respondents who identified glyphosate-resistant weeds on their farms close to the Edgecombe, NC epicenter.

[f] The denominator for the percentage is 8, which is the number of respondents who identified glyphosate-resistant weeds on their farms close to the Terry, TX epicenter.

[g] Number of farmers who used at least one practice in the broad labor category.

[h] Number of farmers who used at least one practice in the broad mechanical/tillage/chemical (MTC) category.

[i] Number of farmers who used at least one practice in the broad cultural category.

[j] Number of farmers who used other herbicide-resistant crops (Liberty Link, Widestrike, and Roundup Ready/Flex).

Corp, 4905 Lakeway Drive, College Station, TX 77840) among the effectiveness ratings provided by respondents and their use of weed-control practices to measure the direction of association (Sheskin 2011).

Results and Discussion

Differences between Periods When GR Weeds Were First Identified. The overall response rate for this survey was 13% (309 usable respondent surveys). Of the 309 respondents, 213 (69%)

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

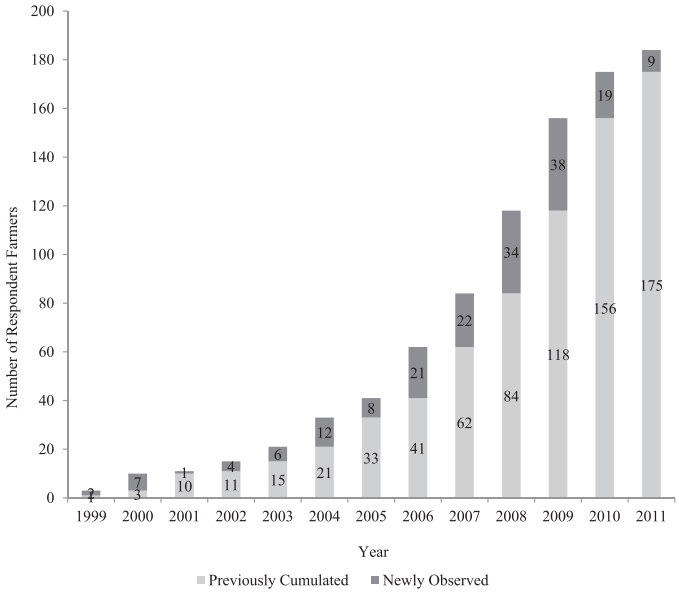


Figure 2. Cumulative distribution of respondents by year in which they first identified glyphosate-resistant weeds on their farms. *Previously cumulated* refers to the previous year's cumulative number of respondents who reported glyphosate-resistant weeds on their farms. *Newly observed* refers to the number of respondents who reported the current year as the year in which they first identified glyphosate-resistant weeds on their farms.

indicated herbicide-resistant weeds identified on their farms. Of the 213 respondents, 184 (86%) reported the GR weeds identified. The 184 respondents were separated into two groups of Weed-A (1995 to 2007), including 84 respondents, and Weed-B (2008 to 2011), containing 100 respondents (Table 1), accounting for 27% and 32% of the overall 309 respondents, respectively. Of the 84 respondents (Weed-A) who identified GR weeds earlier (2007 or earlier), 98% used labor to control them. Meanwhile, 92% of the 100 respondents (Weed-B) who identified GR weeds more recently used labor (Table 2). This result suggests that the former group were more likely to use labor than respondents identifying GR later were ($P = 0.05$). During the earlier years, farmers who identified GR weeds may not have had access to effective GR weed-control options other than labor (Givens et al. 2010). Farmers who identified GR weeds more recently may have taken advantage of improved information about GR weed control gleaned from the earlier experiences of other farmers and the development of more sophisticated (less labor-intensive) weed-control strategies in recent years, although the high proportions of farmers in

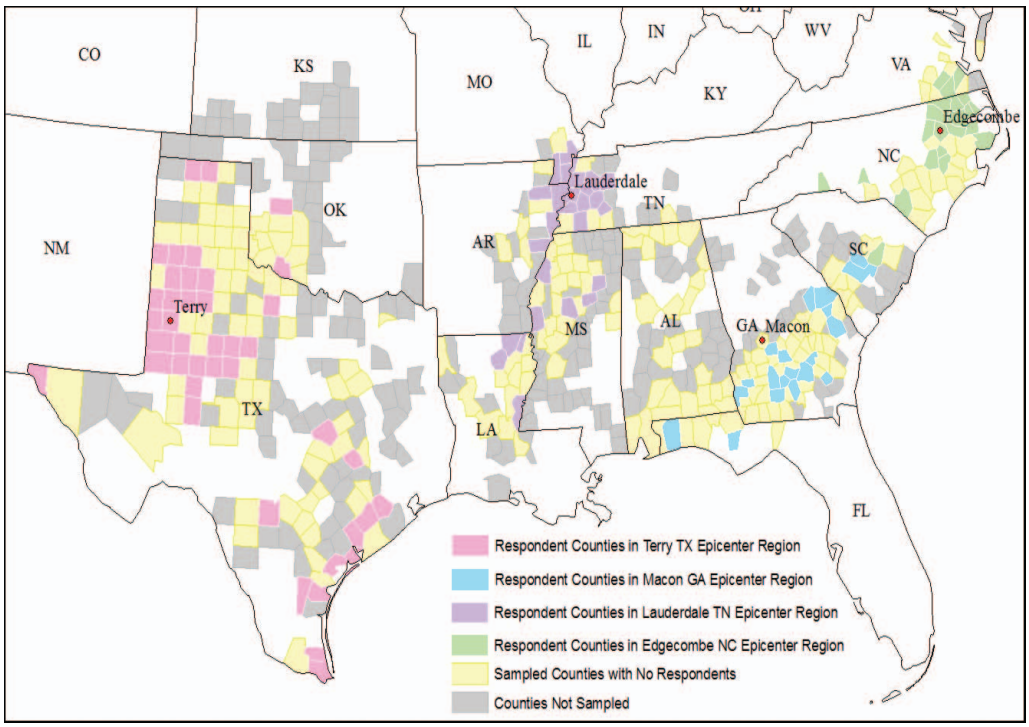


Figure 3. Respondent counties in four epicenter regions for the 2012 weed-resistance survey. (Color for this figure is available in the online version of this article.)

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

both groups suggest that labor-intensive, weed-control practices are still used extensively.

Respondents (95%) who identified GR weeds earlier were more likely to use at least one MTC practice than were those (89%) who identified GR weeds more recently ($P = 0.07$) (Table 2). Within the MTC category, 76% of respondents in Weed-A used hooded sprayers to spot-spray weeds, but 58% of respondents in Weed-B used that practice. Respondents who identified GR weeds earlier were more likely to use the practice than those who identified GR weeds more recently ($P = 0.02$). Respondents (83%) in Weed-A were more likely to change in-season herbicide programs/chemistry than were respondents (60%) in Weed-B ($P < 0.01$). These results suggest that respondents who identified GR weeds earlier on their farms were more likely to use hooded sprayers to spot-spray weeds or to change the in-season herbicide programs/chemistry than were respondents who identified GR weeds more recently. This outcome may correspond with the Johnson and Gibson (2006) finding that 38% of responding corn and soybean growers before 2004 believed that weed resistance was attributed to improper herbicide and chemical application and timing and not to repeated use of glyphosate. Growers who identified GR weeds earlier may have gravitated toward using hooded sprayers and alternative herbicides through trial and error over the years, whereas some of those who identified GR weeds in more-recent years may still be trying other weed-control practices before adopting those practices. By 2010, 73% of responding GR crop (corn, cotton, and soybean) farmers with GR-weed problems used herbicide label rates (Prince et al. 2012).

Many respondents in both Weed-A (86%) and Weed-B (76%) used cultural GR weed-control practices (Table 2), which was primarily caused by a high-percentage application (around 30% or above) in three specific cultural practices, including winter cover crops, crop rotations, and field border management. Scott and VanGessel (2007) conducted a survey on GR horseweed by soybean farmers in Delaware in 2004 and found that 42% of respondents who had GR horseweed in GR soybean production on their farms used crop-rotation management. Foresman and Glasgow (2008) found, in their survey of GR weeds and southern growers in 2006, that one-fifth of the respondents used crop rotations to control those weeds. Crop rotations or cover crops are best management practices recommended by companies and extension services (Green 2007). The high proportion of cultural applications indicates effective education and dissemination of cultural information by extension services, consultants, or companies in the southern United States. This finding is different from the results of Johnson et al. (2009b), who found few farmers perceived crop rotations as effective, in their survey of six states, Indiana, Illinois, Iowa, Nebraska, Mississippi, and North Carolina. In addition, respondents in Weed-A (60%) were more likely to control weeds in field boarders/ditches than were those in Weed-B (35%) ($P = 0.01$). This result indicates that farmers who identified GR weeds earlier may have been more attracted to controlling weeds in field borders/ditches, whereas some respondents who identified GR weeds in more-recent years may still be in the trial-and-error phase.

As a general observation about the results in Table 2, respondents who encountered GR weeds earlier on their farms were more likely to use almost all GR weed-control practices than were farmers with later encounters with GR weeds. Two implications can be drawn from this finding. First, farmers who encountered GR weeds earlier had more time to use additional weed-control practices through trial and error and to adjust to the most-efficient practices for them. Second, respondents encountering GR weeds later may have had less time to adjust or may have learned from others' experiences about the practices that would be most effective for their circumstances. In addition, those respondents encountering GR weeds in 2011 or 2012 may not have had time to respond adequately to the threat or the GR weed problem may not have been overwhelming enough to encourage wholesale control of GR weeds.

Regional Epicenter Differences. Table 3 presents the numbers of respondents who identified GR weeds on their farms, used various GR weed-control practices, and were in the Lauderdale ($n = 79$), Macon ($n = 38$), Edgecombe ($n = 70$), and Terry ($n = 8$) regions. The number of respondents in the Terry region was much lower than it was in the other three regions because GR weeds were only recently found in that region when this survey was conducted in 2012. Results show that significant

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

Table 4. Spearman correlation coefficients between effectiveness rating for resistant weed management practices and the use of each practice for farmers closest to the four epicenters.[a]

Practices used	Spearman correlation coefficients			
	Lauderdale, TN	Macon, GA	Edgecombe, NC	Terry, TX
Number of observations	71	38	70	8
Correlation coefficient				
Labor[b]	0.21*	−0.25	0.06	−0.47
Field scouting	0.21*	0.05	0.10	−0.12
Hand hoeing	0.06	−0.10	−0.08	−0.47
Cleaning harvest equipment	0.07	0.07	0.22*	−0.30
Global positioning system weed mapping	n/a	n/a	−0.21*	n/a
Hand spraying to spot-spraying weeds	0.08	−0.33**	−0.15	−0.30
Collaborating with neighbors	−0.02	−0.13	−0.09	n/a
Others	0.19	n/a	0.18	n/a
Mechanical/tillage/chemical[c]	0.24**	−0.09	−0.01	0.00
Increased conventional tillage	0.02	−0.27	−0.11	0.00
Fall residual herbicide program	−0.08	−0.09	0.02	0.00
Variable rate spray technology	−0.04	−0.21	−0.13	−0.34
Summer fallowed fields	0.07	0.25	n/a	−0.34
Hooded sprayer to spot-spray weeds	−0.01	−0.11	0.01	−0.44
Fall tillage after harvest to kill weeds	−0.03	−0.01	−0.08	−0.30
Changed in-season herbicide program/chemistry	0.17	−0.07	0.19	0.30
Wick applicator/weed wiper	−0.32***	−0.20	−0.12	n/a
Others	0.00	−0.13	0.25**	0.00
Cultural[d]	0.18	−0.03	−0.02	0.47
Other herbicide resistant crops[e]	0.01	−0.43***	−0.20*	n/a
Abandoned part or all of a crop in a field	−0.17	−0.40***	−0.14	0.00
Winter cover crop to suppress weeds	−0.06	0.38***	0.02	n/a
Narrow row spacing	0.05	0.25	0.11	n/a
More crop rotations	−0.16	0.13	−0.07	0.7**
Controlled weeds in field boarders/ditches	0.22*	0.17	0.12	−0.34
Burned field stubble/boarders/ditches	−0.03	0.10	n/a	n/a
High plant population	−0.04	−0.17	n/a	n/a
Others	0.19	n/a	−0.11	n/a

[a] Abbreviation: n/a, not available.

[b] Number of farmers who used at least one practice in the broad labor category.

[c] Number of farmers who used at least one practice in the broad mechanical/tillage/chemical category.

[d] Number of farmers who used at least one practice in the broad cultural category.

[e] Number of farmers who used other herbicide-resistant crops (Liberty Link, Widestrike, and Roundup Ready/Flex).

*** Significant at 0.01; ** significant at 0.05; * significant at 0.10.

differences existed between the Lauderdale and Edgecombe regions for the broad labor category. Significant differences also existed for three specific practices among Lauderdale, Macon, and Edgecombe regions. These results illustrate that a practice used frequently by farmers in one region may be used less frequently in another region because of differences in soil, weather, general production systems (Norsworthy et al. 2012), farmer awareness of the available weed-control practices, and farmers' perceptions about the effectiveness of those practices on their farms.

For the broad labor category (Table 3), respondents (99%) in the Lauderdale region were more likely to use labor practices than respondents (91%) in the Edgecombe region ($P = 0.03$). Regional differences on factors such as the use of labor, history of labor practices, and availability of labor, among other reasons, could account for the labor proportional difference. This result corresponds with the significant Spearman correlation coefficient

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

($\rho = 0.21$, $P = 0.08$) (Table 4) for the Lauderdale region. The correlation indicates that respondents using labor-intensive practices to control GR weeds in the Lauderdale region were more likely to perceive the practices as effective than did those in the other three regions.

Within the labor category (Table 3), significant proportional differences occurred in field scouting, hand hoeing, and hand spraying to spot-spray weeds because of various factors, including history and availability. Respondents (70%) in the Edgecombe region were more likely to use field scouting than were those (49%) in the Lauderdale region ($P = 0.02$) and those (37%) in the Macon region ($P = 0.01$). This difference may be due to the limitations of field scouting. Field scouting is time-consuming, and thus, the associated costs can be high. Farmers may lack knowledge and skills to properly identify weed characteristics and growth stages in a timely manner (Norsworthy et al. 2012). Respondents (96%) in the Lauderdale region were more likely to use hand hoeing than were those (84%) in the Edgecombe region ($P = 0.01$). Respondents (49%) in the Lauderdale region were more likely to use a hand sprayer to spot-spray weeds than were those (31%) in the Edgecombe region ($P = 0.09$). Using a hand sprayer to spot-spray weeds was viewed as ineffective at controlling GR weeds by respondents in the Macon region ($\rho = -0.33$, $P = 0.05$) (Table 4).

Significant positive correlation ($\rho = 0.24$, $P = 0.05$) was found in the Lauderdale region between respondents using at least one weed-control practice in the broad MTC category and their ratings of the effectiveness of GR weed-control practices (Table 4). Thus, respondents who used MTC practices in this region were more likely to perceive those practices as effective in controlling GR weeds, compared with respondents in the other regions, where the correlation coefficients were not significant. Within the MTC category, respondents in the Lauderdale region were more likely (76%) to use a hooded sprayer to spot-spray weeds than were respondents (59%) in the Edgecombe region ($P = 0.03$). Also, respondents (50%) in the Macon region were more likely to use a wick applicator/wiper to control GR weeds than were respondents (11%) in the Edgecombe region ($P = 0.03$) and the Lauderdale region (13%) ($P = 0.03$). The lower proportion of respondents in the Lauderdale region using wick applicators/wipers may be explained by respondents in that region perceiving that practice as ineffective in controlling GR weeds ($\rho = -0.32$, $P = 0.01$) (Table 4). These differences may be influenced by differences in weather, cost, land types, and production systems among the regions.

Within the cultural category (Table 3), respondents (22%) in the Lauderdale region were less likely to use winter cover crops as a GR weed-control method than respondents (53%) in the Edgecombe region ($P = 0.02$). Respondents (39%) in the Macon region used cover crops and rated the practice as an effective method to control GR weeds ($\rho = 0.38$, $P = 0.02$) (Table 4). Respondents (58%) in the Lauderdale region were more likely to control weeds in field borders/ditches than respondents (39%) in the Edgecombe region ($P = 0.06$). In addition, respondents in the Lauderdale region were more likely to perceive the border practices as highly effective ($\rho = 0.22$, $P = 0.07$) (Table 4). This result indicates that respondents from the Lauderdale region placed more merit on managing weeds in field edges, including ditch banks and railroad or power line easements, which are usually managed by government entities or third parties. Coordination of weed control with these entities can be difficult for farmers to achieve (Norsworthy et al. 2012).

Conclusion

This study measured and analyzed the proportional differences across time and region within the southern United States for applying management practices among farmers identifying GR weeds on their farms earlier compared with those identifying weeds on their farms later and among the farmers in the four regions mentioned before. Results across time showed that respondents experiencing GR weeds before 2008 were more likely to use at least one practice in the labor (98%), MTC (95%), or cultural (86%) categories to control GR weeds than were respondents (92%, 89%, and 76%, respectively) experiencing GR weeds between 2008 and 2012. As for specific GR weed-control practices, respondents encountering GR weeds in the earlier period were more likely than those experiencing them in the later period to use hooded sprayers to spot-spray GR weeds (76 vs. 58%), to change in-season herbicide programs and chemicals (83 vs.

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

60%), and to control weeds in the field boarders and ditches (60 vs. 35%).

These results suggest that farmers can reduce the use of ineffective practices and adjust GR weed-control programs to their own circumstances faster if they participate in education programs, developed by extension service personnel or consultants, designed to inform them about the best management practices experienced by their peers and confirmed by research. On the other hand, more-effective communication channels need to be developed among research/extension services and farmers so that farmers experience timely learning about weed management.

The analysis across the Lauderdale, Macon, Edgecombe, and Terry regions shows that respondents in Lauderdale were more likely than farmers in Edgecombe to use broad-labor practices (99 vs. 91%) and specific practices, including hand hoeing (96 vs. 84%), hand spraying (49 vs. 31%), spot spraying (76 vs. 59%), wick applicators (13 vs. 11%), and field-border management (58 vs. 39%). Respondents (50%) in Macon were more likely to use wick applicator/weed wipers than were farmers (11%) in Edgecombe. These differences provide information about preferred management practices for use in developing region-specific Extension education programs to assist producers in implementing appropriate management strategies. Programs could be developed by extension personnel to enhance the use of cover crops in the Macon region because of the high satisfaction regarding the effectiveness of the management practice. Likewise, in the Lauderdale region, programs that promote adoption of controlling weeds in field borders/ditches could be appropriate for farmers who perceive the practice as highly effective.

The contribution of this study is its description and comparison of GR weed management systems across years and regions within the southern United States. Future research should focus on developing new management strategies and education programs for controlling GR weeds and on helping farmers identify the most effective weed-control strategies to use in their particular circumstances.

Literature Cited

Anonymous (2002) Managing Glyphosate-Resistant Weeds—An Investment in Land Value. Syngenta Crop Protection. http://www.syngentacropprotection.com/env_stewardship/resistancemanagement/land_values.pdf. Accessed October 31, 2005

Baldwin F (2011) Going Back in Time for Weed Control. *Delta Farm Press*. http://www.deltafarmpress.com/soybeans/going-back-time-weed-control. Accessed May 22, 2014

Beckie HJ (2006) Herbicide-resistant weeds: management tactics and practices. Weed Technol 20:793–814

Bonny S (2008) Genetically modified glyphosate-tolerant soybean in the USA: adoption factors, impacts and prospects—a review. Agron Sustain Dev 28:21–32

Brandon H (2011) Herbicide resistant weeds cost farmers millions. *Delta Farm Press Blog* February 25. http://deltafarmpress.com/soybeans/herbicide-resistant-weeds-cost-farmers-millions. Accessed November 5, 2015

Cline H. (2013). Palmer Amaranth Resistance Spreads in Texas High Plains. *Southeast Farm Press*. http://www.southwestfarmpress.com/cotton/palmer-amaranth-resistance-spreads-texas-high-plains. Accessed: January 10, 2013

Culpepper AS (2006) Glyphosate-induced weed shifts. Weed Technol 20:277–281

Culpepper AS, York AC, Kichler J (2008) University of Georgia herbicide programs for controlling glyphosate-resistant Palmer amaranth in 2008 cotton. Tifton, GA: Georgia Cooperative Extension Service Circular 924

Dillman DA (1978) Mail and Telephone Surveys: The Total Design Method. New York: Wiley & Sons. 325 p

Duke SO, Powles SB (2008) Mini-review glyphosate: a once-in-a-century herbicide. Pest Manag Sci 64:319–325

Duzy LM, Price AJ, Balkcom KS (2011) Estimating the net returns of managing pigweed in cotton. Pages 336–339 *in* Proceedings of Beltwide Cotton Conference. Cordova, TN: National Cotton Council of America

Foresman C, Glasgow L (2008) US grower perceptions and experiences with glyphosate-resistant weeds. Pest Manag Sci 64:388–391

Franz JE, Mao MK, Sikorski JA (1996) Glyphosate: a unique global pesticide. Washington, DC: American Chemical Society. 653 p

Frisvold GB, Hurley TM, Mitchell PD (2009) Adoption of best management practices to control weed resistance by corn, cotton, and soybean growers. Agbioforum 12:370–381

Givens WA, Shaw DR, Newman ME, Weller SC, Young BG, Wilson RG, Owene MDK, Jorda DL (2011) Benchmark study on glyphosate-resistant cropping systems in the United States, part 3: grower awareness, information sources, experiences and management practices regarding glyphosate-resistant weeds. Pest Manag Sci 67:758–770

Green JM (2007) Review of glyphosate and ALS-inhibiting herbicide crop resistance and resistant weed management. Weed Technol 21:547–558

Green JM (2012) The benefits of herbicide-resistant crops. Pest Manag Sci 68:1323–1331

Harrington J, Byrne PF, Peairs FB, Nissen SJ, Westra P, Ellsworth PC, Fournier AL, Mallory-Smith CA, Zemetra RS, Henry WB (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

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press

Hayes RM, Mueller TC, Willis JB, Montgomery RF (2002) Glyphosate-resistant horseweed and factors influencing its control. Proc South Weed Sci Soc 55:119–120
Heap I (2008) International Survey of Herbicide Resistant Weeds. Weed Science Society of America. http://www.weedscience.org. Accessed June 21, 2014
Holm LG, Plunknett DL, Pancho JV, Herberger JP (1977) The World's Worst Weeds: Distribution and Biology. Honolulu, HI: University Press of Hawaii. 609 p
Johnson WG, Davis VM, Kruger GR, Weller SC (2009a) Influence of glyphosate-resistant cropping systems on weed species shifts and glyphosate-resistant weed populations. Eur J Agron 31:162–172
Johnson WG Gibson KD (2006) Glyphosate-resistant weeds and resistance management strategies: an Indiana grower perspective. Weed Technol 20:768–772
Johnson WG, Owen MDK, Kruger GR, Young BG, Shaw DR, Wilson RG, Wilcut JW, Jordan DL, Weller SC, Bernards ML, Young BG (2009b) U.S. farmer awareness of glyphosate-resistant weeds and resistance management strategies. Weed Technol 23:308–312
Kruger GR, Johnson WG, Weller SC, Owen MDK, Shaw DR, Wilcut JW, Jordan DL, Wilson RG, Bernards ML, Young BG (2009) US grower views on problematic weeds and changes in weed pressure in glyphosate-resistant corn, cotton, and soybean cropping systems. Weed Technol 23:162–166
Laws F (2010) Cotton: 2 Strikes in Weed Resistance. *Southeast Farm Press*. http://www.southeastfarmpress.com/cotton/cotton-2-strikes-weed-resistance. Accessed August 20, 2014
Llewellyn RS, Lindner RK, Pannell DJ, Powles SB (2002) Resistance and the herbicide resource: perceptions of Western Australian grain growers. Crop Prot 21: 1067–1075
Lohr SL (1999) Sampling: Design and Analysis. Pacific Grove, CA: Duxbury Pp 39–42
Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108–113
Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62
Owen MDK, Zelaya IA (2005) Herbicide-resistant crops and weed resistance to herbicides. Pest Manag Sci 61:301–311
Prince JM, Shaw DR, Givens WA, Newman ME, Owen MDK, Weller SC, Young BG, Wilson RG, Jordan DL (2012) Benchmark study, II: a 2010 survey to assess grower awareness of and attitudes toward glyphosate resistance. Weed Technol 26:531–535
Roberson R (2011) Glyphosate resistant pigweed arrives in Virginia. *Southeast Farm Press*. http://www.southeastfarmpress.com/cotton/glyphosate-resistant-pigweed-arrives-virginia. Accessed December 5, 2013
Roberts RK, English BC, Gao Q, Larson JA (2006) Simultaneous adoption of herbicide-resistant and conservation-tillage cotton technologies. J Agric Appl Econ 38:629–643
Robinson E (2010) Old technology coming out of the closet. *Delta Farm Press* http://www.deltafarmpress.com/management/old-technology-coming-out-closet. Accessed October 12, 2014
Rowland MW, Murray DS, Verhalen LM (1999) Full-season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). Weed Sci 47:305–309
Scott BA, VanGessel MJ (2007) Delaware soybean grower survey on glyphosate-resistant horseweed (*Conyza canadensis*). Weed Technol 21:270–274
Sheskin D (2011) Test 29: Spearman's rank-order correlation coefficient. Page 1353 *in* Sheskin DJ, ed., Handbook of Parametric and Nonparametric Statistical Procedures, 5th edn. Boca Raton, FL: Chapman & Hall/CRC
Snedecor GW, Cochran WG (1967) Statistical Methods. 6th edn. Ames, IA: Iowa State University Press. 593 p
StataCorp (2013) Stata Statistical Software: Release 13, College Station, TX: StataCorp
Steckel L (2006) Horseweed. Knoxville, TN: University of Tennessee Extension Fact Sheet 06-0034
Tillé Y (1996) An elimination procedure for unequal probability sampling without replacement. Biometrika 83:238–241
[USDA-NASS] United States Department of Agriculture-National Agricultural Statistics Service (2011) CropScape and Cropland Data Layer. Washington, DC: Department of Agriculture
VanGessel MJ (2001) Glyphosate resistant horseweed from Delaware. Weed Sci 49:703–705
Yancy CH (2003) Glyphosate resistant horseweed causing concern in North Carolina. *Southeast Farm Press*. http://www.southeastfarmpress.com/glyphosate-resistant-horseweed-causing-concern-north-carolina. Accessed November 17, 2014
Zhou X, Larson J A, Lambert DM, Roberts RK, English BC, Bryant KJ, Mishra AK, Falconer LL, Hogan RJ, Johnson JL, Reeves JM (2015) Farmer experience with weed resistance to herbicide in cotton production. Agbioforum 18:1–12

Received April 23, 2015, and approved August 8, 2015.

Associate editor for this paper: Lawrence E. Steckel, University of Tennessee.

https://doi.org/10.1614/WT-D-15-00056.1 Published online by Cambridge University Press