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Farmer Experience with Weed Resistance to Herbicides in Cotton Production

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A mail survey of 2,500 potential cotton farmers in 13 southern cotton-producing states was conducted in 2012 to assess the temporal and geographic extent of weed resistance to herbicides in cotton production, appraise changes in production practices after the emergence of herbicide-resistant weeds, evaluate the effectiveness of those changes in managing resistant weeds, and ascertain the influence of herbicide-resistant weeds on cotton weed-control costs. Over two-thirds of the farmers surveyed reported herbicide-resistant weeds on their farms. Pigweed and horseweed were the dominant resistant weed problems, accounting for 61% and 25% of the responses, respectively. Newly observed infestations of pigweed and horseweed peaked in 2008-2009 and have declined thereafter. Farmers relied extensively on labor-intensive and mechanical/chemical practices to control resistant weeds. The proportion of farmers in the sample who indicated they had total weed control costs of $50 or more per acre nearly doubled with the emergence of herbicide-resistant weeds on their farm.

Key words: weed resistance, herbicides, pigweed, horseweed, labor-intensive practices.

Introduction

No-tillage and conservation tillage practices in cotton (*Gossypium hirsutum*) production have provided substantial benefits to farmers and the environment (Givens et al., 2009; Price et al., 2011). Glyphosate-resistant cotton has been an important factor in the increased adoption of no-tillage and conservation tillage practices (Price et al., 2011; Roberts, English, Gao, & Larson, 2006). However, substantial problems related to weed resistance to glyphosate have developed in cotton and other crops and have created a significant threat to the progress made in the adoption of conservation tillage practices (Price et al., 2011). Cotton growers have experienced more problems with weed resistance given cotton's slower emergence after planting and fewer registered herbicides when compared with other major row crops (Laws, 2010; Norsworthy, Griffith, Scott, Smith, & Oliver, 2008).

Anecdotal reports suggest cotton farmers are abandoning crops due to weed problems, using tillage to control weeds where no-tillage practices had been used previously, relying more on older residual herbicides and sprayer technologies, using non-glyphosate-resistant crops, and devoting more effort to hand hoeing and other labor-intensive practices to manage weeds (Baldwin, 2011; Robinson, 2010; Smith, 2010). Herbicide-resistant (HR) weeds have increased weed control and other production costs and reduced crop yields in some cases (Brandon, 2011; Givens et al., 2011; Rowland, Murry, & Verhalen, 1999; Smith, 2010). Documenting the extent of weed resistance to herbicides in cotton production and the effectiveness of the practices farmers are using to combat the problem can provide guidance in designing strategies to address the problem.

Weed resistance has become a serious problem in crop production because farmers have widely adopted herbicide-tolerant seeds with a concomitant reduction in the use of integrated weed-management practices (Harrington et al., 2009). Previous research surveying farmers about HR weeds has mostly focused on farmer awareness and perceptions about the problem and farmer use of selected weed-control practices to manage herbicide resistance. Surveys of farmers have found that most of them are acutely aware of the potential for weeds to develop resistance to herbicides (Foresman & Glasgow, 2008; Givens et al., 2011; Johnson et al., 2009; Llewellyn, Lindner, Pannell, & Powles, 2002; Prince et al., 2012a). Prior survey research also indicates that farmers have relied on an assortment of chemical and cultural practices to manage weed resistance to herbicides on their farms (Foresman & Glasgow, 2008; Frisvold, Hurley, & Mitchell, 2009; Givens et al., 2011; Johnson & Gibson, 2006; Prince et al., 2012a). Surveys of farmers have also reported that some farmers used more tillage and labor to control HR weeds (Frisvold et al., 2009; Prince et al., 2012a; Johnson & Gibson, 2006).

Notwithstanding the findings of the aforementioned studies, information about when farmers first experienced weed-resistance problems and the geographic extent of those problems has not been documented through a survey of farmers. In addition, the literature on weed resistance has not assessed farmer perceptions of how changes in weed-management practices have affected weed-control costs. The research objectives of this analysis were to 1) assess the temporal and geographic extent of weed resistance to herbicides in cotton production for cotton producers; 2) appraise changes in cotton-farmer production practices due to herbicide resistance and the effectiveness of those practices; and 3) evaluate how changes in production practices to manage weed resistance have influenced cotton weed control costs. To achieve the aforementioned research objectives, a mail survey of cotton farmers in 13 cotton-producing states was conducted in 2012 to provide data about farmer experiences with and adaptations to HR weeds.

Methods and Data

The population of interest was the set of active cotton producers in 13 cotton-producing states: 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, Tennessee (J. Reeves, personal communication, November, 2011).

A random sample of 2,500 cotton farmers (17.9% of the list frame), weighted geographically in relation to the documented cases of weed resistance in four historical outbreak epicenters— Lauderdale County, TN; Nash and Edgecombe Counties, NC; and Macon County, GA—was selected from the list frame to identify the sample of farmers to receive surveys. The sample size corresponds with a 99% confidence interval with a 2% margin of error (Lohr, 1999). The first documented cases of glyphosate-resistant horseweed (*Conyza canadensis*) in cotton were in Lauderdale County in west Tennessee in 2000 (Hayes, Mueller, Willis, & Montgomery, 2002; Steckel, 2006) and in Nash and Edecombe Counties in North Carolina in 2003 (Yancy, 2003). The first confirmed case of glyphosate-resistant pigweed (*Palmer amaranth*) in cotton was in 2005 in central Georgia in Macon County (Culpepper et al., 2006). Glyphosate-resistant pigweed has since been confirmed in Alabama, Arkansas, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia (Culpepper, Whitaker, MacRae, & York, 2008; Duzy, Price, & Balkom, 2011; Roberson, 2011).

A cluster-based sampling strategy was used as the survey sampling design, whereby counties were considered to be primary sampling units. Counties and cotton farmers in a county were jointly and randomly selected using Tillé's (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 a county to total cotton acres in the 13-state region in 2010 (US Department of Agriculture [USDA], National Agricultural Statistics Service [NASS], 2011); 2) the Euclidean distance of the most dense cotton-growing area in a county to the closest one of the four epicenters where weed resistance was initially documented (Lauderdale, TN; Nash and Edgecombe, NC; and Macon, GA); and 3) the number of cotton producers in each county. This sampling strategy ensures that counties producing relatively more cotton were more likely to be selected, with the likelihood of selection discounted by the distance to the nearest original outbreak area. Figures 1 and 2 highlight the geographic distribution of the selection probabilities. Darker shaded counties were assigned higher selection probabilities.

Following Dillman's (1978) mail survey procedures, the questionnaire, a postage-paid return envelope, and a cover letter explaining the purpose of the survey were sent to each randomly selected cotton producer. A post card was first sent to each cotton producer to inform them of the survey questionnaire coming in a week. The initial mailing of the questionnaire was on February 15, 2012, and a reminder post card was sent one week later. A follow-up mailing was sent on March 7, 2012 to cotton producers who did not respond to previous inquiries. The second mailing included a letter restating the importance of the survey, the questionnaire, and a postage-paid return envelope. Finally, the third reminder post card was sent one week later on March 15, 2012.

Of the 2,500 addresses that were randomly selected, 329 individuals responded to the survey and two were undeliverable due to no forwarding address. Among the 329 responses, 20 individuals declined participation because they had retired or no longer produced cotton,

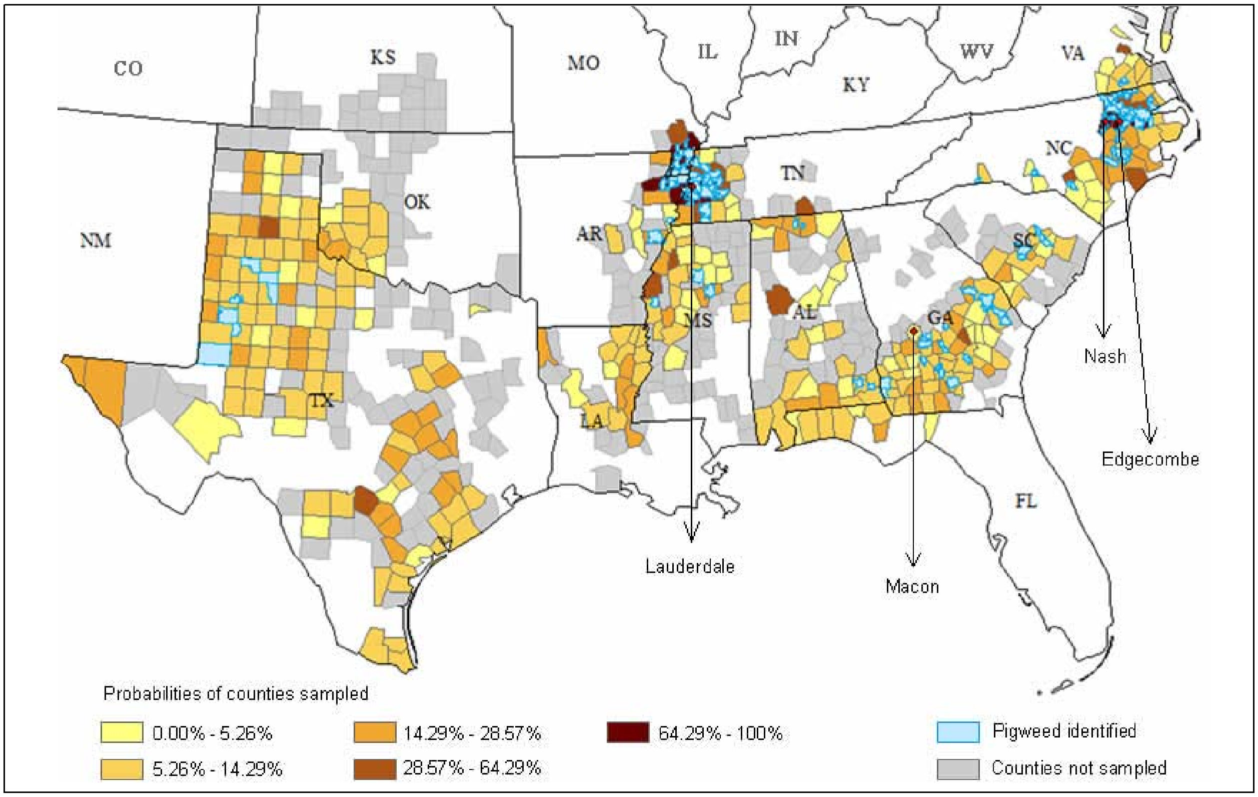

Figure 1. Distribution of pigweed resistance to herbicides reported by farmers in 13 cotton-producing states.

Note: Pigweed resistance to herbicides was identified and reported by one or more farmers in the county. Counties not sampled refer to counties in the list frame that can be selected. The probability of counties selected to receive survey questionnaire were based on three criteria: 1) the proportion of cotton acres in a county to 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 four epicenters where weed resistance was initially documented (Lauderdale County, TN; Nash and Edgecombe, NC; and Macon, GA); and 3) number of cotton producers in each county. This sampling strategy ensures that counties that produced relatively more cotton were more likely to be selected, but the likelihood of selection is discounted by their distance from the original outbreak area.

leaving 309 usable responses. Assuming all remaining non-respondents are active cotton farmers, the total number of cotton farmers surveyed was 2,478 (2,498 − 20) and the survey response rate was 12.47% for the 13-state region (309 ÷ 2,478 = 0.1247 × 100 = 12.47%). Although 309 cotton farmers responded to the survey, some respondents did not answer all survey questions.

To achieve the first research objective, the survey asked farmers when they first heard about weed resistance in their area (i.e., the year), whether HR weeds had been identified on their farm, and what problems they had with herbicide resistance, including weed species identified, cotton area affected, and year first identified on their farm. Responses were analyzed using ArcView (Esri, Redlands, CA) and Stata (StataCorp, College Station, Texas) to assess the temporal and geographic extent of weed resistance to herbicides in cotton production. Frequency counts, percentages, and cumulative percentages of when farmers first heard about weed resistance and reported pigweed and horseweed on their farms were summarized for 1999 through 2011. Mean and total area affected by pigweed and horseweed were also summarized. Spatial distributions of resistant pigweed and horseweed were superimposed on the maps of the selected counties (Figures 1 and 2).

To complete the second research objective, we asked cotton farmers who indicated problems with herbicide resistance about adaptations they made in their cotton-production practices, their perceptions about the effectiveness of those practices, and whom they relied on to develop a plan to manage resistance. Farmers were asked about how their use of tillage practices and HR crops changed with weed resistance. Specifically, farmers were asked to estimate their cotton area in no tillage, reduced tillage, and conventional tillage *before* and *after* the emergence of HR weeds on their farm. Similarly,

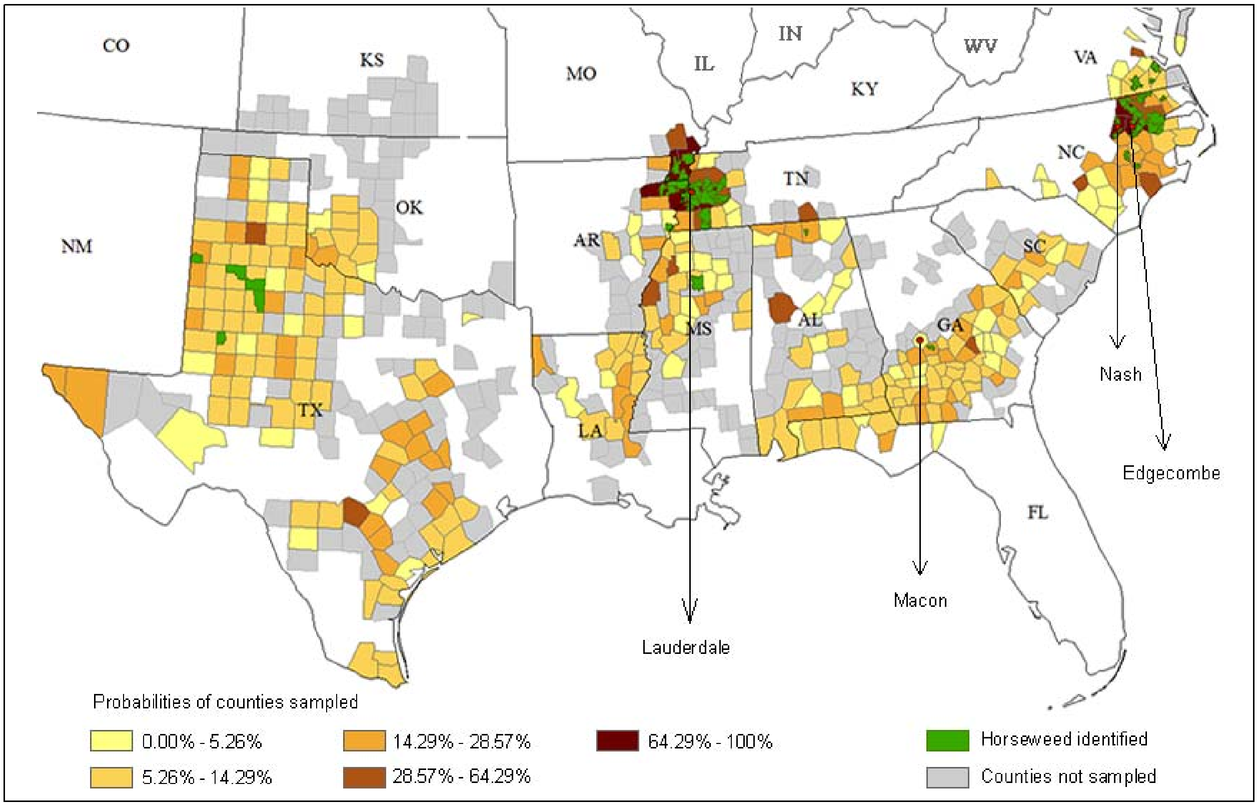

Figure 2. Distribution of horseweed resistance to herbicides reported by farmers in 13 cotton-producing states.
Horseweed resistance to herbicides was identified and reported by one or more farmers in the county. Counties not sampled refer to counties in the list frame that can be selected. The probability of counties selected to receive survey questionnaire were based on three criteria: 1) the proportion of cotton acres in a county to 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 four epicenters where weed resistance was initially documented (Lauderdale County, TN, Nash and Edgecombe, NC, and Macon, GA); and 3) number of cotton producers in each county. This sampling strategy ensures that counties that produced relatively more cotton were more likely to be selected, but the likelihood of selection is discounted by their distance from the original outbreak area.

farmers were asked to estimate the cotton areas *before* and *after* resistant weeds on their farm that were planted in conventional (i.e., non-genetically modified), Liberty Link, Widestrike, and Roundup Ready/Flex cotton. Cotton areas reported by farmers for each of the aforementioned tillage practices and cotton cultivars were aggregated to test for statistical differences *before* and *after* resistant weeds. The null hypothesis was that the aggregated crop area for a practice remained the same *before* and *after* herbicide resistance. For each practice, a 95% confidence interval was estimated for the aggregated cotton area managed *before* resistance and then compared for statistical difference with the aggregated cotton area *after* resistance by a t-test (Cochran, 1977; Stuart & Ord, 1994).

Farmers reporting weed-resistance problems were also asked about other production practices they used to manage herbicide resistance. Farmer responses to the 20 practices were organized into three categories: labor, mechanical/chemical, and cultural practices. These categories were used to evaluate the relative proportions of farmers using the categories to manage weed resistance on their farms. Farmers were also asked to rate on a Likert scale the effectiveness of their management practices (1 = "not effective" to 5 = "very effective"). Finally, farmers were asked to indicate who helped them develop a plan to manage weed resistance—extension/university personnel, crop scouts/consultants, chemical/fertilizer dealers, custom applicators, other farmers, and other sources. Farmers were instructed to check all applicable categories.

To accomplish the third research objective, we asked farmers to indicate their best estimate of total weed-control costs per acre *before* and *after* resistance on their farms by checking one of the following cost categories: \$0-\$49, \$50-\$99, \$100-\$149, \$150-\$199, \$200-\$249,

Table 1. Year when farmers first heard about weed resistance in their area.

Year	Number	%	Cumulative %
Never	29	10	
Checked year, but no specific year	5	2	
1980-1999	10	3	3
2000	9	3	6
2001	2	1	7
2002	4	1	8
2003	7	2	11
2004	15	5	16
2005	27	9	25
2006	26	9	34
2007	22	7	41
2008	56	19	60
2009	57	19	79
2010	18	6	85
2011	11	4	89
Total	298	100	

\$250-\$299, and ≥\$300 per acre. Total weed-control costs were defined broadly in the survey to include "herbicide chemicals and application costs, tillage, labor, hand hoeing, scouting, etc." Proportions of farmers in the *before* and *after* weed resistance samples were calculated for each cost category. A sample proportion test was performed to test for statistical difference in the proportions of farmers *before* and *after* weed resistance (Snedecor & 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 farmers in the weed-cost category *before* and *after* weed resistance, respectively. To test the proportion difference, a *z*-score statistic was calculated as $z = (m_b - m_a)/SE$, where $SE = \{m(1 - m)[(1/n_b)+(1/n_a)]\}^{0.5}$ is the standard error, $m = (m_b n_b + m_a n_a)/(n_b + n_a)$, and n_b and n_a represent the number of farmers in the *before* and *after* resistance samples, respectively. Potential differences in the proportions of farmers reporting weed-control costs in the *before* and *after* resistance groupings were evaluated for the \$0-\$49, ≥\$50, \$0-\$99, and ≥\$100 categories.

Results

Farmers indicated hearing about weed resistance as early as 1980 (n=264, Table 1). However, the number of cotton farmers who first heard about weed resistance increased rapidly after the earliest confirmed reports of glyphosate-resistant horseweed and pigweed in Georgia, North Carolina, and Tennessee in 2000-2005. A previous survey found that only 44% of farmers were aware of glyphosate-resistant weeds in their states in 2005 (Givens et al., 2011), suggesting greater awareness in later years. More than three quarters (79%) of sampled farmers had heard about herbicide resistance in their area by 2009. New instances of farmers hearing about herbicide resistance peaked in 2008 and 2009 and declined thereafter. By 2011, 89% of the sample had learned of weed resistance to herbicides in their area. Another survey in 22 states found similar results, indicating that southern cotton, corn (*Zea mays*), and soybean (*Glycine max*) growers are becoming more aware of glyphosate resistance in their area (Prince et al., 2012a).

A total of 307 farmers responded to the question about whether HR weeds had been identified on the farm. Among these farmers, 213 (69%) indicated that HR weeds had been identified on their farms. Growers in the South more frequently reported glyphosate-resistant weed infestations on their farms (Prince et al., 2012a). In Prince et al.'s (2012a) 2010 survey, only 32% reported experiencing glyphosate-resistant weeds on their farms, the majority of which were in the South (53%). A 2006 survey found that 39% of the 64% who experienced glyphosate resistance were southern growers (Foresman & Glasgow, 2008). Givens et al. (2011) found that 15% had such experience on their own farms in 2005, suggesting that more farmers are experiencing and/or noticing HR weeds as time progresses.

Farmers in the sample indicated that cotton, soybean, and corn were the main crops impacted by weed-resistance problems. The 197 farmers who reported that HR weeds were a problem on their farms identified a total of 349 instances of weed problems on one or more crops. Pigweed was the dominant problem weed (61%), while horseweed was the next most troubling (24%). The remaining instances of problem weeds were ragweed (*Ambrosia*; 5%) and other weeds (10%).

Spatial distributions of reported instances of resistant pigweed and horseweed were superimposed on the maps of county probabilities. Figure 1 reports the distribution of HR pigweed identified by responding farmers. Pigweed resistance to herbicides tended to be clustered around the epicenter counties where resistance was first reported in Lauderdale County, TN, Edgecombe and Nash Counties, NC, and Macon County, GA. Limited instances of pigweed resistance to herbicides were also reported in Texas. The reporting of pigweed resistance to herbicides by cotton farmers in Texas is consistent with recent popular-press reports of HR pigweed appearing in that state (e.g., Smith, 2012). Figure 2

Table 2. Herbicide categories which farmers reported having problems with weed resistance in the sample.

Herbicide category	Respondents [a] Number [b]	Respondents [a] % [b]	Total answers [a] Number	Total answers [a] %
Amino acid synthesis herbicides	191	97	318	91.1
ALS herbicides	13	7	13	3.7
Seedling growth-inhibitor herbicides	3	2	3	0.9
Cell membrane disrupters and organic and arsenicals	2	1	2	0.6
Lipid-synthesis inhibitor herbicides	2	1	2	0.6
Photo-inhibitors herbicides	1	1	2	0.6
Growth-regulator herbicides	1	1	1	0.3
Other	6	3	8	2.3
Total answers			349	100

[a] *197 farmers gave a total of 349 answers of weed resistance to one or more herbicides on their farms.*

[b] *Numbers of respondents do not sum to 197 across herbicide categories and percentages of respondents do not sum to 100% because each respondent can indicate more than one herbicide category.*

shows the distribution of horseweed herbicide resistance identified by survey respondents. Reported horseweed resistance to herbicides tended to be clustered around the epicenter counties where resistance was first reported in Lauderdale County, TN, and Edgecombe and Nash Counties, NC. Limited instances of horseweed were reported in Texas. Fewer horseweed cases were reported in Georgia and South Carolina.

The 197 farmers who reported herbicide-resistance problems indicated one or more herbicides that were ineffective in controlling weeds (n=349, Table 2). Answers were classified by herbicide mode of action (Baumann, Dotray, & Prostko, 1999). Problems with weed resistance to amino acid synthesis herbicides occurred at the highest frequency (318 times). Thus, more than 90% were related to amino acid synthesis herbicides. Glyphosate made up the vast majority of responses classified into the Amino Acid Synthesis Herbicides category. Pigweed and morning glory were reported to be the problematic weeds after glyphosate-resistant cotton adoption (Kruger et al., 2009). Crop area in the sample affected by pigweed and horseweed resistance is presented in Table 3.

Table 3. Crop acres affected by pigweed and horseweed in the sample.

Weed/crop	Number	Mean acres of crops affected	Total acres of crops affected
Pigweed			
Cotton	174	608	105,795
Corn	25	564	14,104
Wheat	5	726	3,632
Peanuts	19	154	2,917
Soybean	76	515	39,145
Total	299		
Horseweed			
Cotton	81	757	61,283
Corn	19	366	6,945
Wheat	1	92	92
Peanuts	5	144	719
Soybean	38	498	18,922
Total	144		

Note: 197 farmers gave 299 answers for crop acres affected by pigweed and 144 answers for crop acres affected by horseweed.

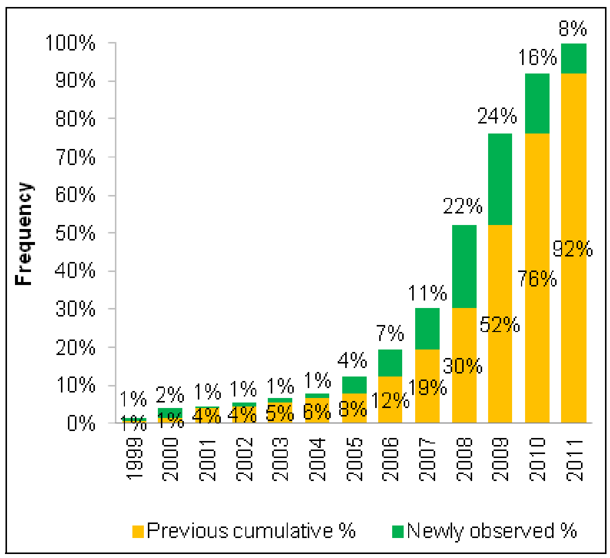

Figure 3. Cumulative distribution of when pigweed was first identified on cotton farms (171 farmers).

Previous cumulative % refers to cumulative percentage of farmers who reported the year when pigweed was first identified on their farms before the current year. Newly observed % refers to percentage of farmers who reported the year when pigweed was first identified on their farms for the current year.

Figure 3 summarizes the frequency and cumulative frequency of the year pigweed was first identified on cotton farms as reported by respondents (n=171). The highest frequency of pigweed first identified on a farm

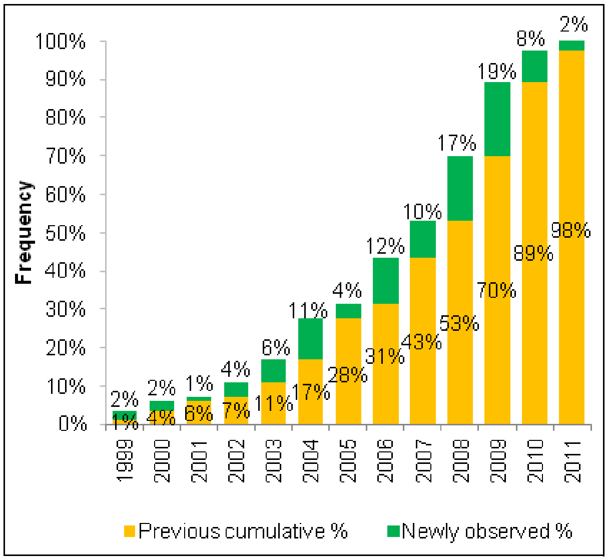

Figure 4. Cumulative distribution of when horseweed was first identified on cotton farms (84 farmers).

Previous cumulative % refers to cumulative percentage of farmers who reported the year when pigweed was first identified on their farms before the current year. Newly observed % refers to percentage of farmers who reported the year when pigweed was first identified on their farms for the current year.

was in 2009 with 49 instances (24%), followed by 2008 with 44 cases (22%), 2010 with 32 cases (16%), 2007 with 22 cases (11%), and 2011 with 16 cases (8%). The number of pigweed resistance problems increased rapidly after the first confirmation of resistant pigweed in Georgia in 2005. Instances of pigweed resistance problems first identified on cotton farms peaked in 2008-2009 and declined thereafter.

Figure 4 summarizes the frequency and cumulative frequency of the year horseweed was first identified on cotton farms (n=84). Similar to the responses for pigweed, the highest frequency of new cases of HR horseweed on cotton farms occurred in 2009 with 16 instances (19%), followed by 2008 with 14 instances (17%), 2006 with 10 instances (12%), and 2004 with 9 instances (11%). Similar to the pattern for HR pigweed, the number of new instances of horseweed resistance problems increased rapidly after initial reports in Tennessee and North Carolina in 2000-2003. New instances of HR horseweed problems peaked in 2008-2009 and declined thereafter.

Figure 5 compares cotton acres produced with no tillage, reduced tillage and conventional tillage *before* and *after* resistance. For no-till cotton, the point estimate of aggregate cotton acres *after* resistance falls below the 95% confidence interval of estimated aggregate cotton acres *before* resistance. For reduced till and

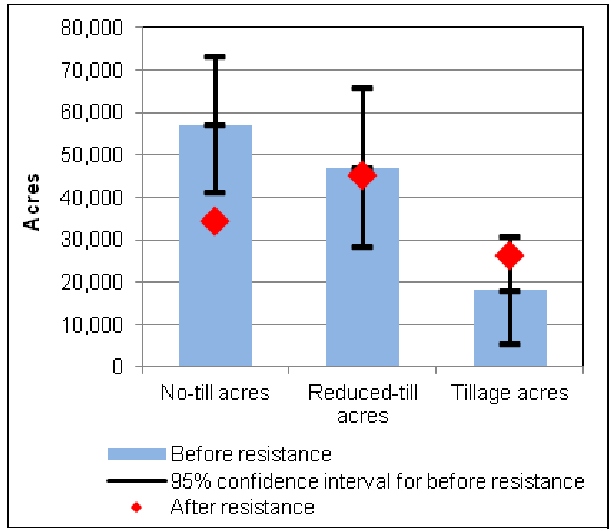

Figure 5. Change in total cotton acres in alternative tillage practices reported by farmers in the sample due to weed resistance to herbicides.

Note: The vertical bars within the "before resistance" category of total cotton acres for each tillage practice in the sample of farmers represent a 95% confidence interval for comparison with the "after resistance" category of total cotton acres for each tillage practice. If the point estimator for total cotton acres after resistance falls outside the 95% confidence interval of estimated total cotton acres before resistance, estimated total cotton acres after resistance were significantly different from the estimated total cotton acres before resistance. If the point estimator for total cotton acres after resistance falls in the 95% confidence interval of estimated total cotton acres before resistance, estimated total cotton acres after resistance were not significantly different from the estimated total cotton acres before resistance.

tillage cotton, however, the point estimate of aggregate cotton acres *after* weed resistance was within the 95% confidence interval of estimated aggregate cotton acres *before* weed resistance. Results suggest that cotton farmers significantly decreased cotton acres in no-till *after* resistance, but did not change the acres produced with reduced till or conventional tillage (Figure 5). Price et al. (2011) concluded that the conservation tillage (including no-tillage) practice was at risk following the emergence and spread of glyphosate-resistant Palmer amaranth because farmers revert back to tilling fields because tillage can control resistant weeds by disrupting weed seed germination (Shrestha, Lanini, Wright, Vargas, & Mitchell, 2006; Steckel, Sprague, Stoller, Wax, & Simmons, 2007).

Figure 6 compares cotton acres in three HR varieties and conventional seed *before* and *after* resistance. For Liberty Link and Widestrike cotton, the point estimate for aggregate cotton acres after weed resistance was above the 95% confidence interval of estimated aggre-

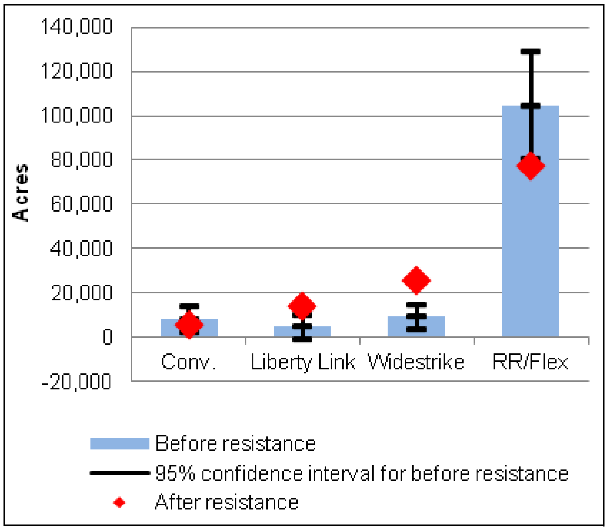

Figure 6. Change in total herbicide-resistant cotton acres in alternative tillage practices reported by farmers in the sample due to weed resistance to herbicides.

Note: RR=Roundup Ready

The vertical bars within the "before resistance" category of total cotton acres for each use of HR cotton crop in the sample of farmers represent a 95% confidence interval for comparison with the "after resistance" category of total cotton acres for each use of HR cotton crop. If the point estimator for total cotton acres after resistance falls outside the 95% confidence interval of estimated total cotton acres before resistance, estimated total cotton acres after resistance were significantly different from the estimated total cotton acres before resistance. If the point estimator for total cotton acres after resistance falls in the 95% confidence interval of estimated total cotton acres before resistance, estimated total cotton acres after resistance were not significantly different from the estimated total cotton acres before resistance.

gate cotton acres *before* resistance. For Roundup Ready/Flex, the point estimate for summed acres after weed resistance falls below the 95% confidence interval of estimated aggregate cotton acres *before* resistance. For conventional cotton, the point estimate of aggregate cotton acres *after* resistance was within the 95% confidence interval of estimated aggregate cotton acres *before* resistance. Results indicate that farmers in the sample significantly increased the use of Widestrike and Liberty Link cotton but decreased the use of Roundup Ready/Flex cotton *after* resistance. Farmers did not change their acres of conventional cotton. Increasing use of Widestrike and Liberty Link cotton but decreasing use of Roundup Ready/Flex cotton suggests that farmers were using other types of weed-resistant cotton so they could use different chemicals for which the weeds were not resistant.

Of the 213 respondents who identified HR weeds on 20 management practices to control resistant weeds (Table 4). The 197 farmers provided a total of 1,154 answers for the practices they used, or an average of 5.6 practices per farmer. Responses were classified into three categories: labor, mechanical/chemical, and cultural practices. Results suggest that farmers relied heavily on labor-intensive practices (41% of the 1,156 answers). Among the individual labor practices, the practice used by the largest number of farmers was hand hoed or pulled weeds (177 of 197 respondents, or 90%), followed by increased field scouting (107 of 197 respondents, or 54%), cleaning harvesting equipment (93 of 197 respondents, or 47%), and hand sprayer to

Table 4. Production practices used by cotton farmers to manage weed resistance.

Practices to manage weed resistance by categories	Farmers	
	Number	%
Labor intensive totals	**475**	**41**
Hand hoed or pulled weeds in field	177	90
Increased field scouting	107	54
Cleaned harvest equipment	93	47
Hand sprayer to spot-spray weeds	78	40
Collaborated with neighbors to control weeds	15	8
GPS weed mapping	1	1
Others	4	2
Mechanical/chemical totals	**479**	**42**
Changed in-season herbicide program/ chemistry	136	69
Hooded sprayer/post-directed herbicides	129	65
Fall tillage after harvest to kill growing weeds	42	21
Wick applicator/weed wiper	37	19
Fall residual herbicide program	24	12
Variable rate spray technology	19	10
Summer fallowed fields	5	3
Others	13	4
Cultural totals	**200**	**17**
Controlled weeds in field boarders/ditches	92	47
Winter cover crop to suppress weeds	71	36
More crop rotations	68	35
Narrower row spacing	15	8
Abandoned part or all of a crop in a field	10	5
Burned field stubble/field boarders/ditches	10	5
Higher plant population	6	3
Others	2	1

Note: 197 farmers gave a total of 1,154 answers for management practices used to control HR weeds on their farms.

Table 5. Information sources used by farmers to develop plans to manage weed resistance.

Source	Number [a]	% of respondents [b]	% of answers [b]
Chemical/fertilizer dealer	117	59	30
Extension/university personnel	105	53	27
Crop scout/ consultant	79	40	20
Other farmers	53	27	14
Other	25	13	6
Custom applicator	8	4	2

[a] *Number of respondents is the same as number of answers for each information source.*

[b] *200 respondents gave 387 answers because each respondent could check more than one information source.*

spot-spray weeds (78 of 197 respondents, or 40%). The finding that farmers extensively relied on labor-intensive practices is consistent with Frisvold et al.'s study (2009). They found that of the best management practices that were widely practiced, more than half were labor intensive.

Cotton producers also extensively relied on mechanical/chemical methods to control weed resistance, which made up 42% of the 1,156 answers. The chemical practice used by the largest number of farmers was a change in in-season herbicide program/chemistry programs (136 of 197 respondents, or 69%). The mechanical practice used by the largest number of farmers was hooded sprayers/post-directed herbicides (129 of 197 respondents, or 65%), followed by fall tillage after harvest to kill growing weeds (42 of 197 respondents, or 21%). Cotton farmers relied to a lesser extent on cultural practices, making up 17% of the 1,156 answers. The cultural practice used by most farmers was controlling weeds in field boarders and ditches (92 of 197 respondents, or 47%), followed by winter cover-crop planting to suppress weeds (71 of 197 respondents, or 36%) and more crop rotations (68 of 197 respondents, or 35%). Johnson et al. (2009) found that the most effective strategy for most farmers to control glyphosate resistance was to use chemicals, followed by using correct label rates. Our results suggest that farmers used various combinations of labor, mechanical/chemical, and cultural practices to manage weed resistance on their farms.

The 200 farmers who reported HR weeds on their farms indicated one or more sources of information used to develop weed-resistance management plans, and they provided 387 answers about the sources of information used (Table 5). Cotton producers used, on average, 1.9 information sources to aid in developing a plan to manage weed resistance. Of these 200 farmers, 59% relied on fertilizer dealers, 53% used extension personnel, 40% used crop scouts and consultants, and 27% used other farmers. Of the 387 answers reported by farmers, fertilizer dealers (30%) and extension personnel (27%) were used the most to develop weed-resistance management plans. Crop scouts and consultants were the third-most cited information source (20%), followed by other farmers (14%).

Table 6. Effectiveness of management practices to control herbicide-resistant weeds.

Effectiveness of management practices	Number	%
Not effective	3	2
Not very effective	12	6
Neutral	55	30
Effective	85	46
Very effective	31	17
Total	186	100

Note: 186 farmers rated the effectiveness of management practices.

Table 6 summarizes the 5-point-scale ratings of management-practice effectiveness used to control HR weeds. Among the 213 farmers who identified HR weeds on their farm, 186 farmers rated the effectiveness of their management practices; 17% rated their strategies as very effective, 46% rated them as effective; 30% rated efforts as neutral; and 6% rated their practices as not very effective. Only 2% rated their efforts as ineffective. Thus, 63% of the 186 responding farmers rated their altered weed-management practices as either effective or very effective. Similarly, of the growers Prince et al. (2012b) found experiencing glyphosate-resistant weeds, 67% reported that their modifications were very effective or somewhat effective in controlling HR weeds. The most effective practices in their study (rated 9 or 10 on scale of 1 [least effective] to 10 [most effective]) were chemical and cultural methods—using correct label rate (62%), rotating crops (37%), and rotating herbicide chemistries (34%).

A total of 166 farmers identified the total weed-control cost categories that best fit their farm situation *before* and *after* the onset of weed resistance on their farms (Figure 7). Total weed-control costs were defined broadly in the survey to include "herbicide chemicals and application costs, tillage, labor, hand hoeing, scouting, etc." Results from the proportional difference tests indicated that the proportion of farmers in the $0-$49 cost category was significantly smaller *after* resistance

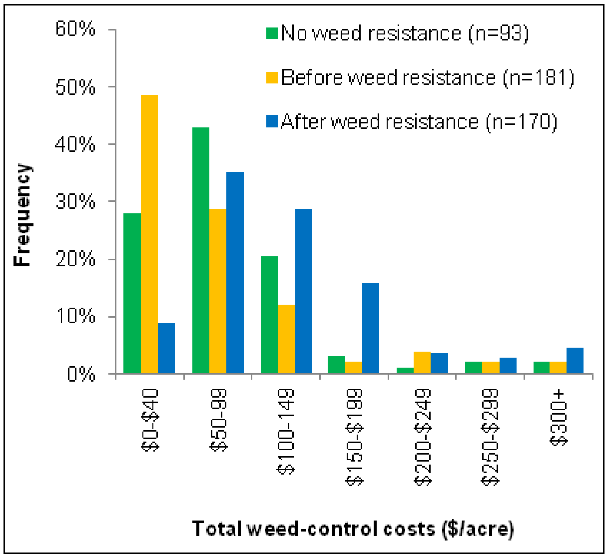

Figure 7. Total weed-control costs for cotton reported by farmers with and without weed resistance on their farms.

(m_b = 0.52, m_a = 0.08, n_b = 87, n_a = 13, *z*-score = 3.00, *p*-value < 0.01) and the proportion of farmers in the ≥$50 cost categories was significantly larger *after* resistance (m_b = 0.48, m_a = 0.92, n_b = 79, n_a = 154, *z*-score = -7.65, *p*-value < 0.01). About half (48%) of the respondents reported total weed-control costs ≥$50 per acre *before* HR weeds first appeared on their farms, while 92% of the respondents indicated they had weed-control costs ≥$50 per acre *after* weed resistance.

Similarly, results from the proportional difference tests indicated that the proportion of farmers in the $0-$99 cost categories was significantly lower *after* resistance (m_b = 0.81, m_a = 0.44, n_b = 135, n_a = 73, *z*-score = 5.46, *p*-value < 0.01), and the proportion of farmers in the ≥$100 cost categories was significantly higher *after* resistance (m_b = 0.19, m_a = 0.56, n_b = 31, n_a = 93, *z*-score = -3.61, *p*-value < 0.01). About one-fifth (19%) of the respondents had total weed-control costs of $100 or more *before* resistance, but 56% of the respondents reported weed-control costs ≥$100 *after* resistance. In summary, our results suggest that a larger proportion of farmers in the sample reported an increase in weed-control costs *after* the emergence of HR weeds. The percentage of farmers in the sample who indicated they had total weed-control costs ≥$50 per acre nearly doubled with the emergence of HR weeds on their farms.

Conclusions

More than two-thirds of the farmers surveyed experienced HR weeds on their farms. Pigweed was the dominant weed problem, followed by horseweed, ragweed, and other non-specific weeds. Newly observed infestations of pigweed and horseweed peaked in 2008-2009 and declined thereafter. The geographic and temporal distributions of specific HR weeds may be useful for university/extension personnel, crop consultants, and fertilizer dealers to communicate with farmers about how to more effectively manage HR pigweed and horseweed.

Although most farmers were aware that widespread use of herbicide-tolerant seeds encouraged the emergence of resistant weeds, some farmers tried alternative herbicide-tolerant seeds to prevent resistant weeds. This research will enhance opportunities for university/extension personnel, crop consultants, and fertilizer dealers to provide more accurate information to help farmers make decisions about avoiding and/or managing HR weeds.

Labor-intensive practices are the most frequently used practices to control weed resistance to herbicides, followed by cultural practices and then chemical and mechanical/tillage methods. At times, labor-intensive practices to manage resistant weeds can influence farmers to abandon cotton production due to intensive labor requirements (Smith, 2010). Therefore, university/extension personnel, crop consultants, and fertilizer dealers could help some farmers by providing alternative integrated management practices that best fit different production systems.

Weed-control costs significantly increased after the emergence of HR weeds. The percentage of farmers in the sample who indicated they had total weed-control costs of $50 or more per acre nearly doubled with the emergence of HR weeds on their farms. Future research should evaluate which management practices are most cost-effective in adapting to HR weed infestations and how to effectively assist farmers to adopt those practices.

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