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Resistance of Enlist™ (AAD-12) Cotton to Glufosinate

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Enlist™ cotton contains the *aad-12* and *pat* genes that confer resistance to 2,4-D and glufosinate, respectively. Thirty-three field trials were conducted focused on Enlist cotton injury from glufosinate as affected by cotton growth stage, application rate, and single or sequential applications. Maximum injury from a single application of typical 1X (542 g ae ha^{-1}) and 2X use rates was 3 and 13%, respectively, regardless of growth stage. Injury from sequential applications of 1X or 2X rates was equivalent to single applications. Similar injury was observed with four commercial formulations of glufosinate. Cotton yield was never affected by glufosinate. This research demonstrates Enlist™ cotton has robust resistance to glufosinate at rates at least twice the typical use rate when applied once or twice at growth stages ranging from 2 to 12 leaves.

Nomenclature: Glufosinate; 2,4-D; cotton, *Gossypium hirsutum* L.
Key words: Aryloxyalkanoate dioxygenase, DAS-81910-7, herbicide-resistant crops, phosphinothricin acetyltransferase.

Herbicide resistance is a serious problem in the United States and other developed countries and threatens our ability to economically and sustainably produce food and fiber. Biotypes of weeds resistant to 19 of the 26 known herbicide mechanisms of action have been confirmed in the United States, and biotypes resistant to 23 of the mechanisms have been confirmed globally (Heap 2016). In the US Cotton Belt, glyphosate-resistant (GR) Palmer amaranth (*Amaranthus palmeri* S. Wats.) is the most widespread and economically damaging resistant weed (Culpepper et al. 2010; Ward et al. 2013), although there are also problems with GR biotypes of common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], goosegrass [*Eleusine indica* (L.) Gaertn.], horseweed [*Conyza canadensis* (L.) Cronq.], johnsongrass [*Sorghum halepense* (L.) Pers.], Italian ryegrass [*Lolium perenne* L. spp. *multiflorum* (Lam.) Husnot], and kochia [*Kochia scoparia* (L.) Schrad.] (Heap 2016). Weed biotypes resistant to acetyl CoA carboxylase inhibitors, acetolactate synthase (ALS) inhibitors, microtubule assembly inhibitors, nucleic acid inhibitors, protoporphyrinogen oxidase inhibitors, photosystem I electron diverters, and photosystem II electron transport inhibitors are also present in the Cotton Belt (Heap 2016).

As incidences of resistance continue to increase, growers have fewer options to control weeds. Residual herbicides are consistently recommended in cotton weed management programs, especially for Palmer amaranth (Culpepper 2016; Wilson et al. 2011; York 2016). However, POST topically applied herbicides are needed in these programs for the control of emerged Palmer amaranth plants, as PRE herbicides alone will not adequately control this weed (Culpepper and York 1997; Keeling et al. 1991; Riar et al. 2011; Whitaker et al. 2011). Currently available POST options to control GR Palmer amaranth in cotton are limited to pyrithiobac, trifloxysulfuron, and glufosinate. Pyrithiobac and trifloxysulfuron are ALS inhibitors, and multiple resistance to both glyphosate and ALS inhibitors is common (Heap 2016, Poirier et al. 2014, Sosnoskie et al. 2011).

Glufosinate can control Palmer amaranth (Corbett et al. 2004), but control is often inadequate in a

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glufosinate-only program (Merchant et al. 2014; Whitaker et al. 2011; Wilson et al. 2007). However, if glufosinate is applied in a timely manner and used in conjunction with residual soil-applied herbicides, Palmer amaranth can be controlled well (Cahoon et al. 2015; Everman et al. 2009; Gardner et al. 2006). With the advent of GR Palmer amaranth, cotton growers are increasingly relying on glufosinate applied multiple times per season (Sosnoskie and Culpepper 2014). Increased reliance on glufosinate has raised concerns over the increased selection pressure for glufosinate-resistant biotypes (Burgos et al. 2015; Jalaludin et al. 2015; York 2016).

Widespread evolution of herbicide-resistant weed biotypes has created an imperative for alternative weed management strategies, including additional herbicide mechanisms of action (Hay 1999). Unfortunately, herbicides with new mechanisms of action are not being developed (Duke 2012). Crops that contain traits conferring resistance to existing herbicides previously not used in the crop, or resistance to multiple herbicide mechanisms of action, can expand the utility of existing herbicide technologies and enable new management solutions (Beckie 2014; Green and Owen 2011; Green 2012).

Enlist™ cotton (DAS-81910-7) was developed using *Agrobacterium*-mediated transformation to stably insert the transformation plasmid pDAB4468 into a conventional cotton variety. The inserted binary pDAB4468 plasmid contains two gene cassettes. The first cassette contains the aryloxyalkanoate dioxygenase-12 (*aad-12*) gene, and the second cassette contains the phosphinothricin acetyltransferase (*pat*) gene, each under the control of constitutive promoters (USDA-APHIS 2013). The *aad-12* gene and the *pat* gene simultaneously encode for the aryloxyalkanoate dioxygenase-12 and phosphinothricin acetyltransferase enzymes, which confer resistance to the herbicides 2,4-D and glufosinate, respectively (USFDA 2014). The original transformant was subsequently used in a standard plant breeding regimen to produce the experimental varieties utilized in the experiments reported herein.

There are no currently published data on resistance of Enlist cotton to glufosinate. Our objective was to determine the resistance to glufosinate conferred by the Enlist cotton trait as affected by glufosinate rate, single or sequential glufosinate application, and cotton growth stage at application.

Materials and Methods

Thirty-three field experiments were conducted across the major cotton-producing areas of the United States in 2010 through 2013 and in 2016 (Table 1). An experimental cotton variety containing the Enlist cotton event of interest (DAS-81910-7) was planted at the rate of 13 seeds per meter of row into weed-free conventionally tilled seedbeds. Plots were four rows wide (91- to 97-cm row spacing) by 6 m long. Treatments were arranged in a randomized complete block design and replicated four times. Each location received a PRE herbicide, with herbicide selection based on historic weed populations, soil type, and local practice. After cotton emergence, plots were kept weed-free through the use of mechanical cultivation and removal of weeds by hand. Other production practices, including fertilization, insect control, plant growth regulator application, and defoliation, were performed according to local practice. Treatment variables (glufosinate rate, timing of application, formulation of glufosinate) were applied to the center two rows of each plot, leaving a two-row unsprayed buffer between treatments.

Treatments in 2010 consisted of glufosinate-ammonium (Liberty® 280 SL herbicide, Bayer CropScience LP, Research Triangle Park, NC 27709) applied once to 6- to 8-leaf cotton at rates of 542, 1,084, and 2,168 g ae ha^{-1}. The typical (1 ×) glufosinate use rate for cotton is 542 g ha^{-1} (Anonymous 2016). Treatments in 2011 included a single application of glufosinate at 542 and 1,084 g ha^{-1} to 6- to 8-leaf cotton or 10- to 12-leaf cotton, and sequential applications of the same rates at each growth stage. The time interval between 6- to 8-leaf and 10- to 12-leaf applications ranged from 11 to 16 d, depending upon location. Treatments in 2012 and 2013 were similar to those in 2011, except that a third rate of glufosinate, 804 g ha^{-1}, was included during the single and sequential application timings.

An experiment at four locations in 2016 (Table 1) focused on Enlist cotton response to four commercial products containing 24.5% (w/v) glufosinate-ammonium. Commercial brands included Cheetah® herbicide (Nufarm, Inc, 11901 S. Austin Ave., Alsip, IL 60803), Interline® herbicide (United Phosphorus, Inc., 630 Freedom Business Center, Suite 402, King of Prussia, PA 19406), Kong® Glufosinate 280 herbicide (Solera ATO, LLC, 12230 E. Del Norte,

Table 1. Location, soil type, and planting and harvest dates of field experiments.

Year	Location	Coordinates	Soil series	Planting date	Harvest date
2010	Headland, AL	31.38°N, 85.31°W	Lucy loamy sand[a]	20-May	28-Oct
	Jacksonville, AR	34.80°N, 92.09°W	Rilla silt loam[b]	2-Jun	18-Oct
	Fresno, CA	36.72°N, 119.93°W	Pachappa loam[c]	25-May	NH[n]
	Attapulgus, GA	30.76°N, 84.48°W	Lucy loamy sand	3-Jun	NH
	Brinson, GA	30.97°N, 84.70°W	Blanton loamy sand [d]	25-May	29-Oct
	Winsboro, LA	32.14°N, 91.69°W	Egypt silt loam[e]	24-May	29-Sep
	Greenville, MS	33.27°N, 91.03°W	Commerce silt loam[f]	24-May	23-Aug
	Verona, MS	34.17°N, 88.74°W	Leeper fine sandy loam[g]	8-Jun	17-Oct
	Lewiston, NC	36.14°N, 77.18°W	Rains sandy loam[h]	1-Jun	29-Oct
	Elko, SC	33.41°N, 81.33°W	Wagram sand [i]	8-Jun	9-Oct
	Memphis, TN	35.12°N, 89.81°W	Waverly silt loam[j]	28-May	8-Nov
2011	North Little Rock, AR	34.80°N, 92.09°W	Rilla silt loam	31-May	26-Oct
	Brinson, GA	30.97°N, 84.70°W	Blanton loamy sand	18-May	12-Oct
	Greenville, MS	33.27°N, 91.03°W	Commerce silt loam	19-May	14-Oct
	Jackson Springs, NC	35.19°N, 79.69°W	Candor sand[k]	27-May	10-Oct
	Halfway, TX	34.16°N, 101.95°W	Olton clay loam[l]	19-May	NH
	Lubbock, TX	33.70°N, 101.81°W	Olton clay loam	18-May	NH
	Memphis, TN	35.12°N, 89.81°W	Waverly silt loam	1-Jun	25-Oct
2012	Brinson, GA	30.97°N, 84.70°W	Blanton loamy sand	9-May	16-Oct
	Winnsboro, LA	32.14°N, 91.69°W	Egypt silt loam	15-May	22-Oct
	Greenville, MS	33.27°N, 91.02°W	Commerce silt loam	10-May	10-Oct
	Verona, MS	34.17°N, 88.74°W	Leeper fine sandy loam	16-May	11-Oct
	Jackson Springs, NC	35.67°N, 78.51°W	Candor sand	23-May	12-Oct
	Hale Center, TX	34.15°N, 101.95°W	Pullman clay loam[m]	18-May	30-Oct
	Elko, SC	33.41°N, 81.33°W	Wagram sand	9-May	30-Nov
2013	Brinson, GA	30.97°N, 84.70°W	Blanton loamy sand	22-May	28-Oct
	Greenville, MS	33.27°N, 91.02°W	Commerce silt loam	29-May	9-Oct
	Verona, MS	34.17°N, 88.74°W	Leeper fine sandy loam	29-May	24-Oct
	Jackson Springs, NC	35.20°N, 79.69°W	Candor sand	29-May	8-Nov
2016	Brinson, GA	30.97°N, 84.70°W	Blanton loamy sand	04-May	29-Sep
	Greenville, MS	33.27°N, 91.02°W	Commerce silt loam	06-May	23-Sep
	Verona, MS	34.17°N, 88.74°W	Leeper fine sandy loam	11-May	21-Sep
	Elko, SC	33.41°N, 81.33°W	Wagram sand	26-May	13-Oct

[a] Loamy, kaolinitic, thermic Arenic Kandiudults

[b] Fine-silty, mixed, active, thermic Typic Hapludalfs

[c] Coarse-loamy, mixed, active, thermic Mollic Haploxeralfs

[d] Loamy, siliceous, semiactive, thermic Grossarenic Paleudults

[e] Fine-silty, mixed, active, thermic Aquic Glossudalfs

[f] Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts

[g] Fine, smectitic, nonacid, thermic Vertic Epiaquepts

[h] Fine-loamy, siliceous, semiactive, thermic Typic Paleaquults

[i] Loamy, kaolinitic, thermic Arenic Kandiudults

[j] Coarse-silty, mixed, active, acid, thermic Fluvaquentic Endoaquepts

[k] Sandy, kaolinitic, thermic Grossarenic Kandiudults

[l] Fine, mixed, superactive, thermic Aridic Paleustolls

[m] Fine, mixed, superactive, thermic Torrertic Paleustolls

[n] Abbreviation: NH, not harvested.

Yuma, AZ 85367), and Liberty 280 SL. Each herbicide was applied to 2- to 4-leaf cotton at 542 and 1,084 g ha^{-1} and repeated at the same rates 12 to 15 d later, when cotton had six to eight leaves.

In all trials, glufosinate was applied using CO$_2$-pressurized backpack sprayers delivering a spray volume of 140 L ha^{-1}. Sprayers were equipped with TeeJet® Drift Guard flat-fan spray tips in 2010 through 2012, and with TeeJet Air Induction Extended Range flat-fan tips in 2013 and 2016 (TeeJet Technologies, Glendale Heights, IL). Crop injury was estimated visually as described by Frans et al. (1986) at 3, 7, and 14 d after application (DAA) using a scale of 0% (no injury) to 100% (complete crop death). Foliar chlorosis and necrosis and growth reduction were considered when estimating injury. Plots were mechanically harvested to determine seed cotton yield, and data were converted to lint yield assuming a 38% gin turnout.

Statistical Analysis. A linear mixed model (ANOVA) was fit using the **lme4** package in R version 3.2.1 (The R Foundation for Statistical Computing, c/o Institute for Statistics and Mathematics, Wirtschaftsuniversität Wien, Welthandelsplatz, 1020 Vienna, Austria). In the model, herbicide treatment was the fixed effect and trial location, year, and replication were random effects. To satisfy ANOVA assumptions, visual crop injury estimates and yields were subjected to a Box-Cox transformation (Box and Cox 1964) using the **car** package in R, which determined the power transformation that maximized the log likelihood function for each response variable. However, we present back-transformed data, with means rounded to whole numbers and means separations based on transformed data. Where the ANOVA test indicated that treatment effects were significant, means were separated at $\alpha = 0.05$ using Tukey's honest significant difference test. Lint yields of glufosinate-treated cotton were compared to the yield of nontreated cotton using Dunnett's procedure (Dunnett 1955).

Results and Discussion

In 2010, Glufosinate at the 1 × rate of 542 g ha^{-1} applied to 6- to 8-leaf cotton injured the crop only 3% at 3 DAA, and no injury was perceptible at 14 DAA (Table 2). Glufosinate at 2 × and 4 × rates of 1,084 and 2,168 g ha^{-1} injured cotton 7% and 13%, respectively, at 3 DAA. Injury decreased over time, and only 2% injury was noted with the 4 × rate at 14 DAA. In all trials in 2010 and subsequent years, injury was expressed primarily as foliar necrosis along with minor chlorosis. No reduction in cotton growth was noted. Cotton lint yield was unaffected by glufosinate.

Table 2. Injury and yield of Enlist cotton following a single POST application of glufosinate at the 6- to 8-leaf growth stage in 2010.[a]

Glufosinate rate	Injury 3 DAA[b]	Injury 7 DAA	Injury 14 DAA	Lint yield[c]
g ha^{-1}	%	%	%	kg ha^{-1}
0				965
542	3 a	2 a	0 b	970
1,084	7 b	4 b	0 b	1,000
2,168	13 c	10 c	2 a	970

[a] Data for injury and yield averaged over 11 and 9 locations, respectively. Means within a column followed by the same letter are not different according to Tukey's honest significant difference test ($\alpha = 0.05$).

[b] Abbreviation: DAA, days after application.

[c] Yield of glufosinate-treated cotton did not differ from yield of nontreated cotton according to Dunnett's procedure ($\alpha = 0.05$).

In 2011, glufosinate at 542 g ha^{-1} injured 6- to 8-leaf cotton and 10- to 12-leaf cotton 1% to 2% at 3 DAA, while glufosinate at 1,084 g ha^{-1} caused 5% to 6% injury at 3 DAA (Table 3). Similar injury was noted when glufosinate was applied to 6- to 8-leaf cotton and 10- to 12-leaf cotton. Injury from sequential applications was initially no greater than was injury from the 10- to 12-leaf application. However, greater injury was noted with sequential applications 7 d after the second application compared with that observed with one application to 10- to 12-leaf cotton. However, injury 7 DAA was only 10%. No injury was observed with single or sequential applications of 1 × and 2 × rates at 14 DAA. No glufosinate treatment impacted cotton yield in 2011.

Injury observed in 2012 and 2013 was similar to that observed in 2011. Glufosinate at 542, 804, and 1,084 g ha^{-1} injured cotton 3%, 5% to 6%, and 7% to 9%, respectively, at 3 DAA (Table 3). The crop was injured only 3% by the highest rate of glufosinate at 14 DAA. Glufosinate applied sequentially to 6- to 8-leaf and 10- to 12-leaf cotton was no more injurious than was glufosinate applied only to 10- to 12-leaf cotton. Regardless of application rate, growth stage at application, or number of applications, cotton yield was not impacted by glufosinate.

No differences in cotton injury were noted among the four brands of glufosinate applied at 542 g ha^{-1} to 2- to 4-leaf cotton or 6- to 8-leaf cotton at 3, 7, or 14 DAA (Table 4). When glufosinate was applied at 1,084 g ha^{-1} to 2- to 4-leaf cotton, injury was 8% or

Table 3. Injury and yield of Enlist cotton following single and sequential POST applications of glufosinate in 2011, 2012, and 2013.[a]

Cotton growth stage at application	Glufosinate rate	Injury[b] 2011 DAA[c] 3	7	14	2012–2013 DAA 3	7	14	Lint yield[d] 2011	2012-2013
	g ha^{-1}	%						kg ha^{-1}	
	0							1,220	1,535
6- to 8-leaf	542	1 b	1 c	0 a	3 c	2 a	1 c	1,265	1,530
6- to 8-leaf	804				5 abc	4 a	2 b		1,520
6- to 8-leaf	1,084	5 ab	2 b	1 a	9 a	6 a	3 ab	1,135	1,525
10- to 12-leaf	542	2 ab	2 b	0 a	3 c	2 a	1 c	1,130	1,545
10- to 12-leaf	804				6 abc	4 a	1 c		1,525
10- to 12-leaf	1,084	6 a	4 b	1 a	7 abc	6 a	3 ab	1,145	1,505
6- to 8- fb[c] 10- to 12-leaf	542 fb 542	2 ab	10 a	0 a	4 bc	2 a	1 c	1,150	1,485
6- to 8- fb 10- to 12-leaf	804 fb 804				7 abc	5 a	2 b		1,530
6- to 8- fb 10- to 12-leaf	1,084 fb 1,084	5 ab	10 a	1 a	8 ab	6 a	4 a	1,140	1,520

[a] Injury and yield data averaged over 7 and 5 locations, respectively, in 2011. Injury and yield data averaged over 11 locations in 2012 and 2013. Means within a column followed by the same letter are not different according to Tukey's honest significant difference test ($\alpha = 0.05$).

[b] Injury for sequential applications recorded following the second application.

[c] Abbreviations: DAA, days after application; fb, followed by.

[d] Yield of glufosinate-treated cotton did not differ from yield of nontreated cotton according to Dunnett's procedure ($\alpha = 0.05$).

less. Significantly higher levels of injury were noted with Interline and Liberty than were with Kong at 3 DAA, and at 7 DAA cotton treated with Interline had significantly more injury than did that treated with Kong. The same response was noted 3 DAA to 6- to 8-leaf cotton, with no significant differences between glufosinate brands except that more injury was observed with Interline than with Kong. No differences among glufosinate brands were noted 7 or 14 DAA to 6- to 8-leaf cotton. No glufosinate treatment reduced cotton yield compared with the no-glufosinate treatment.

This research demonstrates that Enlist cotton has robust resistance to glufosinate at rates at least twice the

Table 4. Injury and yield of cotton with four brands of glufosinate applied at the 2- to 4-leaf growth stage and re-applied at the 6- to 8-leaf growth stage in 2016.[a]

Glufosinate brand	Rate	Cotton injury days after 2- to 4-leaf application 3	7	14	days after 6- to 8-leaf application 3	7	14	Lint yield[b]
	g ha^{-1}	%						kg ha^{-1}
No glufosinate								1,148
Cheetah	542	3 bc	2 bc	1 ab	4 ab	3 a	0 a	1,198
Cheetah	1,084	5 ab	4 ab	1 ab	7 a	4 a	1 a	1,167
Interline	542	3 bc	2 bc	2 ab	3 ab	2 a	0 a	1,229
Interline	1,084	8 a	6 a	3 a	7 a	5 a	1 a	1,151
Kong	542	1 c	0 c	0 b	2 b	2 a	1 a	1,210
Kong	1,084	3 bc	1 bc	0 b	3 ab	4 a	1 a	1,149
Liberty	542	4 ab	2 bc	0 b	3 ab	3 a	0 a	1,164
Liberty	1,084	8 a	5 ab	2 ab	7 a	5 a	1 a	1,176

[a] Data averaged over four locations. Means within a column followed by the same letter are not different according to Tukey's honest significant difference test ($\alpha = 0.05$).

[b] Yield of glufosinate-treated cotton did not differ from yield of nontreated cotton according to Dunnett's procedure ($\alpha = 0.05$).

typical use rate when applied once or twice at growth stages ranging from 2- to 12-leaf. Resistance was similar to that described in previous research with LibertyLink and GlyTol + LibertyLink cotton (Dodds et al. 2015; Irby et al. 2013; Sweeney and Jones 2014; Wallace et al. 2011). In other work (Richburg et al. 2015; Dow AgroSciences internal research reports, unpublished data), Enlist cotton has been shown to be very tolerant to 2,4-D applied topically. With resistance to both glufosinate and 2,4-D, Enlist cotton will give growers more options for controlling GR weeds. Mixtures of glufosinate plus 2,4-D will improve consistency of weed control (Chahal and Johnson 2012; Craigmyle et al. 2013; Johnson et al. 2010; Merchant et al. 2013, 2014; Steckel et al. 2006). Additionally, co-application of glufosinate and 2,4-D will delay evolution of resistance to both herbicides (Diggle et al. 2003; Powles et al. 1997).

Literature Cited

Anonymous (2016) Liberty 280 SL herbicide product label. Bayer CropScience Publication No. US84473405C 160222C 04/16. Research Triangle Park, NC: Bayer CropScience. 25 p

Beckie HJ (2014) Herbicide resistance in weeds and crops: challenges and opportunities. Pages 347–364 *in* Chauhan BS, Mahajan G. eds. Recent Advances in Weed Management. New York: Springer

Box GEP, Cox DR (1964) An analysis of transformations. J Royal Stat Soc, Series B 26:211–252

Burgos NR, Scott BC, Nichols RL (2015) Tolerance profiles and mechanism of tolerance to glufosinate in Palmer amaranth from Arkansas. Page 25 *in* Proceedings of the 2015 Southern Weed Science Society annual meeting. Savannah, GA: Southern Weed Science Society

Cahoon CW, York AC, Jordan DL, Seagroves RW (2015) Cotton response and Palmer amaranth control with mixtures of glufosinate and residual herbicides. J Cotton Sci 19:622–630

Chahal GS, Johnson WG (2012) Influence of glyphosate or glufosinate combinations with growth regulator herbicides and other agrochemicals in controlling glyphosate-resistant weeds. Weed Technol 26:638–643

Corbett JL, Askew SD, Thomas WE, Wilcut JW (2004) Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, and sulfosate. Weed Technol 18:443–453

Craigmyle BD, Ellis JM, Bradley KW (2013) Influence of herbicide programs on weed management in soybean with resistance to glufosinate and 2,4-D. Weed Technol 27:78–84

Culpepper AS (2016) Weed management in cotton. Pages 90–144 *in* Georgia Cotton Production Guide. CSS-15-01. Athens, GA: The University of Georgia Cooperative Extension Service. http://www.ugacotton.com/vault/file/2016-UGA-Cotton-Production-Guide.pdf. Accessed October 8, 2016

Culpepper AS, Webster TM, Sosnoskie LM, York AC (2010) Glyphosate-resistant Palmer amaranth in the United States. Pages 195–212 *in* Nandula VK, ed. Glyphosate Resistance in Crops and Weeds: History, Development, and Management. Hoboken, NJ: John Wiley & Sons

Culpepper AS, York AC (1997) Weed management in no-tillage bromoxynil-tolerant cotton (*Gossypium hirsutum*). Weed Technol 11:335–345

Diggle AJ, Neve PB, Smith FP (2003) Herbicides used in combination can reduce the probability of herbicide resistance in finite weed populations. Weed Res 43:371–382

Dodds DM, Main CL, Barber LT, Burmester C, Collins GD, Edmisten K, Stephenson DO 4th, Whitaker JR, Boykin DL (2015) Response of LibertyLink and WideStrike cotton to varying rates of glufosinate. Weed Technol 29:665–674

Duke SO (2012) Why have no new herbicide modes of action appeared in recent years? Pest Manage Sci 68:505–512

Dunnett CW (1955) A multicomparisons procedure for comparing several treatments with a control. J Am Stat Assoc 50: 1096–1121

Everman WJ, Clewis SB, York AC, Wilcut JW (2009) Weed control and yield with flumioxazin, fomesafen, and *S*-metolachlor systems for glufosinate-resistant cotton residual weed management. Weed Technol 23:391–397

Frans RE, Talbert R, Marx D, Crowley H (1986) Experimental design and techniques for measuring and analyzing plant responses to weed control practices. Pages 29–46 *in* Camper ND, ed. Research Methods in Weed Science. Champaign, IL: Southern Weed Science Society

Gardner AP, York AC, Jordan DL, Monks DW (2006) Management of annual grasses and *Amaranthus* spp. in glufosinate-resistant cotton. J Cotton Sci 10:328–338

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

Green JM, Owen MDK (2011) Herbicide-resistant crops: utilities and limitations for herbicide-resistant weed management. J Agric Food Chem 59:5819–5829

Hay JV (1999) Herbicide discovery in the 21st century - a look into the crystal ball. Pages 55–65 *in* Brook GT, Roberts TR, eds. Pesticide Chemistry and Bioscience. The Food-Environment Challenge. Cambridge, UK: Royal Society of Chemistry

Heap I (2016) The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org. Accessed October 7, 2016

Irby JT, Dodds DM, Reynolds DB, Main CL, Barber LT, Smith KL, Stewart AM (2013) Evaluation of GlyTol™ and GlyTol™ + LibertyLink® cotton in the Mid-South. J Cotton Sci 17:131–139

Jalaludin A, Yu Q, Powles SB (2015) Multiple resistance across glufosinate, glyphosate, paraquat and ACCase-inhibiting herbicides in an *Eleusine indica* population. Weed Res 55:82–89

Johnson B, Young B, Matthews J, Marquardt P, Slack C, Bradley K, York A, Culpepper S, Hager A, Al-Khatib K, Steckel L, Moechnig M, Loux M, Bernards M, Smeda R (2010) Weed control in dicamba-resistant soybeans. Crop Manag. doi: 10.1094/CM-2010-0920-01-RS. Accessed October 16, 2016

Keeling JW, Siders KT, Abernathy JR (1991) Palmer amaranth (*Amaranthus palmeri*) control in a conservation tillage system for cotton (*Gossypium hirsutum*). Weed Technol 5:137–141

Merchant RM, Culpepper AS, Eure PM, Richburg JS, Braxton LB (2014) Controlling glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in cotton with resistance to glyphosate, 2,4-D, and glufosinate. Weed Technol 28:291–297

Merchant RM, Sosnoskie LM, Culpepper AS, Steckel LE, York AC, Braxton LB, Ford JC (2013) Weed response to 2,4-D, 2,4-DB, and dicamba applied alone or with glufosinate. J Cotton Sci 17:212–218

Poirier AH, York AC, Jordan DL, Chandi A, Everman WJ, Whitaker JR (2014) Distribution of glyphosate- and thifensulfuron-resistant Palmer amaranth (*Amaranthus palmeri*) in North Carolina. Int J Agron. doi: 10,1155/2014/747810

Powles SB, Preston C, Bryan IB, Jutsum AR (1997) Herbicide resistance: impact and management. Adv Agron 58:57–93

Riar DS, Norsworthy JK, Griffith GM (2011) Herbicide programs for enhanced glyphosate-resistant and glufosinate-resistant cotton (*Gossypium hirsutum*). Weed Technol 25:526–534

Richburg JS, Braxton B, Haygood BB, Huckaba R, Lovelace M, Perry DH, Thompson GD, Viator R, Walton LL (2015) Tolerance of Enlist cotton to Enlist Duo, 2,4-D choline and glufosinate: a multi-year research summary. Page 269 *in* Proceedings of the 2015 Southern Weed Science Society Annual Meeting. Savannah, GA: Southern Weed Science Society

Sosnoskie LM, Culpepper AS (2014) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) increases herbicide use, tillage, and hand-weeding in Georgia cotton. Weed Sci 62:393–402

Sosnoskie LM, Kichler JM, Wallace RD, Culpepper AS (2011) Multiple resistance in Palmer amaranth to glyphosate and pyrithiobac confirmed in Georgia. Weed Technol 59:321–325

Steckel LE, Craig CC, Hayes RM (2006) Glyphosate-resistant horseweed (*Conyza canadensis*) control with glufosinate prior to planting no-till cotton (*Gossypium hirsutum*). Weed Technol 20:1047–1051

Sweeney JA, Jones MA (2014) Glufosinate tolerance of multiple WideStrike and Liberty-Link cotton (*Gosspyium hirsutum* L.) cultivars. Crop Sci 55:403–410

[USDA-APHIS] US Department of Agriculture–Animal and Plant Health Inspection Service (2013) Dow AgroSciences Petition for Determination of Nonregulated Status for Herbicide Tolerant DAS-81910-7 Cotton. https://www.aphis.usda.gov/brs/aphisdocs/13_26201p.pdf. Accessed October 11, 2016

[USFDA] US Food and Drug Administration (2014) Biotechnology Consultation Note to the File BNF No. 000142. http://www.fda.gov/Food/FoodScienceResearch/GEPlants/Submissions/UCM427610. Accessed October 11, 2016

Wallace RD, Sosnoskie LM, Culpepper AS, York AC, Edmisten KL, Patterson MG, Jones MA, Crooks HL, Cloud GL, Pierson J (2011) Tolerance of GlyTol® and GlyTol® + LibertyLink® cotton to glyphosate and glufosinate in the southeastern U. S. J Cotton Sci 15:80–88

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*). Weed Technol 27:12–27

Whitaker JR, York AC, Jordan DL, Culpepper AS (2011) Weed management with glyphosate- and glufosinate-based systems in PHY 485 WRF cotton. Weed Technol 25:183–191

Wilson DG Jr, York AC, Jordan DL (2007) Effect of row spacing on weed management in glufosinate-resistant cotton. Weed Technol 21:489–495

Wilson RG, Young BG, Matthews JL, Weller SC, Johnson WG, Jordan DL, Owen MDK, Dixon PM, Shaw DR (2011) Benchmark study on glyphosate-resistant cropping systems in the United States. Part 4: Weed management practices and effects on weed populations and soil seed banks. Pest Manag Sci 67:771–780

York AC (2016) Weed Management in Cotton. 2016 Cotton Information. Raleigh, NC: North Carolina Cooperative Extension Service Publ. AG-417. Pp 84–129

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