Weed Technology 2017 31:666–674
© Weed Science Society of America, 2017

Glufosinate plus Dicamba for Rescue Palmer Amaranth Control in XtendFlex™ Cotton

Rachel A. Vann, Alan C. York, Charles W. Cahoon Jr, Trace B. Buck, Matthew C. Askew, and Richard W. Seagroves*

Cotton growers commonly use glufosinate-based programs to control glyphosate-resistant Palmer amaranth. Palmer amaranth must be small (≤7.5 cm) for consistent control by glufosinate, and growers often miss the optimum application timing. XtendFlex™ cotton may provide growers a tool to control larger Palmer amaranth. Glufosinate, dicamba, and glufosinate plus dicamba were compared for Palmer amaranth control in a rescue situation. Herbicides were applied to 16- to 23-cm weeds (POST-1) followed by a second application (POST-2) 12 d later. Glufosinate-ammonium at 590 g ai ha^{-1} plus dicamba diglycolamine salt at 560 g ae ha^{-1} POST-1 followed by glufosinate plus dicamba POST-2 was more effective than glufosinate at 880 g ha^{-1} POST-1 followed by glufosinate at 590 g ha^{-1} POST-2 or dicamba alone applied twice. Following a directed layby application of glyphosate, diuron, and *S*-metolachlor 14 d after POST-2, Palmer amaranth was controlled 99% by any system containing dicamba or glufosinate plus dicamba POST-1 followed by dicamba, glufosinate, or glufosinate plus dicamba POST-2 compared with 87% to 91% control by glufosinate alone applied twice. Cotton height and number of main stem nodes at layby were reduced in systems with dicamba only POST-1 followed by dicamba or glufosinate plus dicamba POST-2, presumably due to competition from the slowly dying Palmer amaranth with dicamba only POST-1. These treatments also delayed cotton maturity and reduced lint yield compared with systems containing glufosinate plus dicamba at POST-1.

Nomenclature: Dicamba; diuron; glufosinate; glyphosate; *S*-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Watts; cotton, *Gossypium hirsutum* L.

Key words: Cotton-fiber quality, cotton injury, cotton maturity, early-season weed competition, weed biomass.

Palmer amaranth is the most troublesome weed in cotton and other agronomic crops in the southern United States (Culpepper et al. 2010; Webster 2013). The biology of this weed, its impact on cotton yield, and control difficulties in cotton have been reviewed previously (Culpepper et al. 2010; Steckel 2007; Ward et al. 2013). Palmer amaranth can dramatically reduce cotton yield (MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999) and interfere with or prevent mechanical harvest (Morgan et al. 2001; Smith et al. 2000).

Glyphosate-resistant (GR) cotton was commercialized in 1997, allowing growers to effectively and conveniently control Palmer amaranth and other weeds with glyphosate (Culpepper and York 1998, 1999). Growers quickly adopted the technology. In 2000, 49% to 76% of the cotton in the southeastern states of Alabama, Georgia, North Carolina, South Carolina, and Virginia was planted to a GR cultivar (USDA Agricultural Marketing Service [USDA-AMS] 2001). In the same year, 22% of the cotton in Missouri, 43% to 54% of the cotton in Arkansas, Louisiana, and Mississippi, and 81% of the cotton in Tennessee was planted to a GR cultivar (USDA-AMS 2001). By 2005, 92% to 99% of the cotton in each of the aforementioned states was planted to a GR cultivar (USDA-AMS 2006). Growers reduced or eliminated use of other herbicides and relied

---

DOI: 10.1017/wet.2017.68

* First, second, fourth, fifth, and sixth authors: Graduate Research Assistant, William Neal Reynolds Professor Emeritus, Undergraduate Assistant, Undergraduate Assistant, and Research Specialist, Crop and Soil Sciences Department, Box 7620, North Carolina State University, Raleigh, NC 27695-7620; third author: Assistant Professor, Eastern Shore Agricultural Research and Extension Center, Virginia Tech, Painter, VA 23240. Corresponding author's E-mail: raatwell@ncsu.edu

https://doi.org/10.1017/wet.2017.68 Published online by Cambridge University Press

heavily or totally on glyphosate for weed control (Shaner 2000; Wilson et al. 2011). Widespread planting of GR cotton and extensive reliance on glyphosate led to selection for glyphosate resistance in Palmer amaranth and other species. Palmer amaranth resistant to glyphosate was first confirmed in Georgia in 2005 (Culpepper et al. 2006) and has since been confirmed in 27 states (Heap 2017). Resistant biotypes are widespread across the Southeast and Mid-South regions of the United States (Culpepper et al. 2010). Palmer amaranth resistant to acetolactate synthase (ALS)-inhibiting herbicides is also prevalent, and multiple resistance to both glyphosate and ALS-inhibiting herbicides is common (Heap 2017; Sosnoskie et al. 2011; Ward et al. 2013). In North Carolina, 95% of the Palmer amaranth populations contain at least some individuals resistant to both glyphosate and ALS-inhibiting herbicides (Poirier et al. 2014).

In an attempt to control GR Palmer amaranth, growers have returned to use of residual herbicides applied preplant, PRE, and POST (Sosnoskie and Culpepper 2014). Residual herbicides are important components of cotton weed management programs, but POST herbicides are still required for adequate control (Everman et al. 2009; Gardner et al. 2006). With most of the Palmer amaranth being resistant to glyphosate and ALS-inhibiting herbicides, and with protoporphyrinogen oxidase inhibitor-resistant Palmer amaranth being reported in several states (Heap 2017; Salas et al. 2016), growers have few POST herbicide options. Many growers are now depending upon glufosinate-based programs, which integrate residual herbicides with timely POST applications of glufosinate to effectively control Palmer amaranth (Cahoon et al. 2015a; Culpepper et al. 2009; Sosnoskie and Culpepper 2014). However, Palmer amaranth must be 7.5-cm tall or less for consistent control by glufosinate (Culpepper 2016; York 2017). Palmer amaranth grows rapidly (Bond and Oliver 2006; Horak and Loughin 2000), and growers often struggle to make timely applications. Adverse weather conditions or equipment breakdowns can force growers into making rescue applications, often with inadequate control of the weed (Barnett et al. 2013; Corbett et al. 2004).

Bollgard II® XtendFlex™ cotton, tolerant of dicamba, glufosinate, and glyphosate, may offer growers a new opportunity to control Palmer amaranth in a rescue situation. Co-application of dicamba plus glufosinate has been more effective on larger Palmer amaranth than either herbicide applied alone (Cahoon et al. 2015b; Merchant et al. 2013; York et al. 2012). The objective of this experiment was to compare glufosinate alone, dicamba alone, and co-application of glufosinate plus dicamba for Palmer amaranth control in a rescue situation and the subsequent effects on cotton growth and yield.

Materials and Methods

The experiment was conducted in two separate fields each year on the Central Crops Research Station, Clayton, NC (35.67°N, 78.51°W) during 2015 and 2016. The experiment also was conducted at the Upper Coastal Plain Research Station, Rocky Mount, NC (35.90°N, 77.68°W) and the Eastern Shore Agricultural Research and Extension Center, Painter, VA (37.59°N, 75.82°W) in 2016. The combination of location and year comprised an environment. Soils at each environment are described in Table 1. Each environment was in a conventional tillage system. All environments had

Table 1. Soil characteristics by environment.

Environment	Soil series	Textural classification	Soil subgroup	Soil pH	Humic matter[a]
					%
Clayton A, 2015	Norfolk	Loamy sand	Typic Kandiudults	6.0	0.36
Clayton B, 2015	Wedowee	Loamy sand	Typic Kanhapludults	5.9	0.41
Clayton C, 2016	Norfolk	Loamy sand	Typic Kandiudults	6.4	0.27
Clayton D, 2016	Wedowee	Loamy sand	Typic Kanhapludults	5.6	0.32
Rocky Mount, 2016	Aycock	Very fine sandy loam	Typic Paleudults	5.9	0.36
Painter, 2016	Bojac	Sandy loam	Typic Hapludults	6.4	1.00

[a] Soil pH and humic matter determined by the North Carolina Department of Agriculture and Consumer Services, Agronomic Division. Humic matter was determined photometrically according to Mehlich (1984).

https://doi.org/10.1017/wet.2017.68 Published online by Cambridge University Press

Table 2. Cotton planting, herbicide application, and cotton harvest dates by environment.

		Herbicide applications			
Environment	Cotton planting	First POST	Second POST	Layby	Cotton harvest
Clayton A, 2015	May 13	June 4	June 16	July 1	October 20
Clayton B, 2015	May 7	May 29	June 10	June 24	October 26
Clayton C, 2016	May 11	June 8	June 20	July 13	November 4
Clayton D, 2016	May 2	June 1	June 13	July 6	October 28
Rocky Mount, 2016	April 26	June 8	June 20	July 13	November 2
Painter, 2016	June 2	June 29	July 11	August 8	November 8

natural GR Palmer amaranth infestations exceeding 100 plants m^{-2}. No PRE herbicides were applied to ensure heavy Palmer amaranth densities for POST treatments. Some environments also had annual grasses that were controlled as needed with clethodim applied at 100 g ai ha^{-1} (Select Max®, Valent USA, Walnut Creek, CA) plus crop oil concentrate at 1% (v/v) (Agri-Dex®, Helena Chemical Company, Collierville, TN).

Dyna-Gro® cotton '3385 B2XF' (Crop Production Services, Loveland, CO) was planted in 2015. Dyna-Gro® cotton '3526 B2XF' was planted in 2016 at both environments in Clayton and in Rocky Mount. Cotton 'DP 1538 B2XF' (Monsanto, St Louis, MO) was planted in 2016 at Painter, VA. Cotton planting and harvest dates are in Table 2.

The experimental design was a randomized complete block with five replications at the Clayton A, 2015 environment, four replications at the other environments in Clayton and Rocky Mount, and three replications at Painter. Plot size was four rows by 9.1 m at Clayton and Rocky Mount and four rows by 6.1 m at Painter. Row spacing was 97 cm at Clayton and 91 cm at Rocky Mount and Painter.

Treatments consisted of combinations of glufosinate, dicamba, and glufosinate plus dicamba applied POST twice. Palmer amaranth size at the first POST application (POST-1) ranged from 5- to 25-cm tall, with the predominant size being 16 cm in 2015. In 2016, Palmer amaranth at POST-1 ranged from 5 to 35 cm, with the predominant size being 23 cm. Cotton was in the 1- to 2-leaf stage at POST-1 in 2015 and the 2- to 3-leaf stage in 2016. The POST-1 application was followed by a second POST application (POST-2) 12 d later. Application dates are given in Table 2. Application rates included glufosinate-ammonium (Liberty® 280SL, Bayer CropScience, Research Triangle Park, NC) at 590 or 880 g ha^{-1} and dicamba diglycolamine salt (Clarity®, BASF Ag Products, Research Triangle Park, NC) at 560 g ha^{-1}. Specific treatments are listed in Table 3; a nontreated check was also included. All plots except the nontreated checks also received a directed layby application of glyphosate potassium salt (Roundup PowerMax®, Monsanto) at 1,260 g ae ha^{-1} plus *S*-metolachlor (Dual Magnum®, Syngenta Crop Protection, Greensboro, NC) at 1,070 g ai ha^{-1} plus diuron (Direx® 4L, ADAMA, Raleigh, NC) at 1,120 g ai ha^{-1} 14 to 15 d after POST-2 application (DAP2) in 2015 or 23 to 28 DAP2 in 2016. The POST herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 165 kPa. When glufosinate was applied alone, DG TeeJet® 11002 Drift Guard nozzles (TeeJet Technologies, Wheaton, IL) were used. When dicamba was applied alone or co-applied with glufosinate, TTI 110015 Turbo TeeJet® Induction nozzles (TeeJet Technologies) were used. Layby herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 206 kPa with a single flood nozzle (TK-VS2 FloodJet® wide angle flat-spray nozzle, TeeJet Technologies) per row middle.

Palmer amaranth control and cotton injury (primarily foliar necrosis) were estimated visually using a 0 to 100 scale (Frans et al. 1986) at 7 and 12 d after POST-1 (DAP1) at North Carolina environments or 10 DAP1 at Painter, 14 DAP2, and 14 d following the layby application (DALB). Height of 20 cotton plants plot^{-1} was recorded at layby at all environments. The number of cotton main stem nodes at layby and cotton height 30 DALB were recorded from 20 randomly selected plants at all North Carolina environments. Palmer amaranth aboveground fresh biomass was collected in September from three row middles in treated plots (17 to 25 m^2) and 1 m^2 in the nontreated plots. In mid-September to early October, 10 cotton plants plot^{-1} at North Carolina environments were randomly selected

https://doi.org/10.1017/wet.2017.68 Published online by Cambridge University Press

Table 3. Palmer amaranth control and biomass as affected by glufosinate and dicamba applied POST.[a,b]

Treatments				Palmer amaranth control				Palmer biomass[d]
Herbicides		Application rates						
POST-1	POST-2	POST-1	POST-2	7 DAP1	10–12 DAP1[c]	14 DAP2[b]	14 DALB[b]	
		g ha^{-1}		%				kg ha^{-1}
Gluf	Gluf	590	590	74 b	66 c	79 c	87 c	1552 a
Gluf	Gluf	880	590	83 ab	77 b	84 bc	91 b	1170 a
Gluf + Dic	Gluf	590 + 560	590	89 a	91 a	93 a	99 a	196 b
Gluf + Dic	Gluf	880 + 560	590	92 a	94 a	95 a	99 a	33 b
Gluf + Dic	Gluf + Dic	590 + 560	590 + 560	—[e]	—	97 a	99 a	184 b
Gluf + Dic	Gluf + Dic	880 + 560	590 + 560	—	—	97 a	99 a	23 b
Dic	Dic	560	560	56 c	76 b	81 c	99 a	90 b
Dic	Gluf + Dic	560	590 + 560	—	—	92 a	99 a	67 b
Dic	Gluf + Dic	560	880 + 560	—	—	93 a	99 a	37 b

[a] Abbreviations: DAP1, days after POST-1, DAP2, days after POST-2; DALB, days after layby; Dic, dicamba; Gluf, glufosinate.

[b] Data for control at 7 DAP1 averaged over five North Carolina environments. Other data averaged over six environments. Means within a column followed by the same letter are not different at $P \leq 0.05$ based on Fisher's protected LSD.

[c] Palmer amaranth control recorded at 10 DAP1 at Painter, VA, environment and 12 DAP1 at North Carolina environments.

[d] Palmer amaranth biomass in nontreated check averaged 23,000 kg ha^{-1}.

[e] Data (—) combined over POST-1 applications at 7 DAP1 and 10–12 DAP1.

to determine boll production and percentage of open bolls. Treated plots were mechanically harvested for seed cotton yield (Table 2). Cotton in nontreated checks could not be harvested due to the severe weed infestations, and yield was assumed to be zero. A sample of harvested seed cotton was collected from each plot and ginned to determine lint percentage. This lint percentage was used to convert seed cotton yield to lint yield. Each lint sample was analyzed for fiber strength, fiber length, fiber length uniformity, and micronaire using high-volume instrument analysis by Cotton Incorporated in Cary, NC.

Statistical analyses were performed using the PROC Mixed procedure in SAS (v. 9.3; SAS Institute, Cary, NC). The use of the method = type3 option in PROC Mixed allows for the evaluation of random by fixed interaction terms and provides better control of type I error rates than the default REML estimation (Moore and Dixon 2015; Stroup and Littell 2002). All data met model assumptions. Treatments were considered a fixed factor, and replication and environment were considered random factors. Treatment and environment did not interact for cotton height at layby, cotton nodes, total bolls, percent open bolls, lint yield, or any fiber-quality parameter, and therefore combined analyses occurred. A treatment by environment interaction for Palmer amaranth control, Palmer amaranth biomass, and cotton height 30 DALB merited further investigation to ascertain whether treatments were uniform over environments. The treatment mean square was at least 3-fold greater than the treatment by environment interaction mean square, providing justification to combine over environments. Additionally, environments were analyzed individually; similar trends existed among environments, further justifying combined analyses. Treatment means were reported using least-squares means. Nontreated checks were excluded from statistical analyses.

Results and Discussion

Palmer Amaranth Control. Differences among treatments were observed with Palmer amaranth control at 7 DAP1, 10 to 12 DAP1, 14 DAP2, and 14 DALB ($P \leq 0.001$ for each). Glufosinate was similarly effective applied at 590 or 880 g ha^{-1}, in combination with dicamba, and controlled Palmer amaranth 89% to 92% at 7 DAP1 and 91% to 94% at 10 to 12 DAP1 (Table 3). Mixtures of glufosinate plus dicamba were more effective than glufosinate at either rate applied alone or dicamba alone. Merchant et al. (2013) also reported greater control of 15- to 25-cm Palmer amaranth by combinations of

https://doi.org/10.1017/wet.2017.68 Published online by Cambridge University Press

glufosinate plus dicamba compared with either herbicide applied alone. Palmer amaranth control by glufosinate alone declined 6% to 8% between 7 DAP1 and 10 to 12 DAP1. This was attributed to regrowth on plants escaping control. Inadequate control of Palmer amaranth greater than 7.5 cm is well documented (Culpepper et al. 2009, 2010; Whitaker et al. 2011). In contrast, control by mixtures of glufosinate plus dicamba was similar at 7 and 10 to 12 DAP1, while control by dicamba alone increased 20% during this period. Dicamba kills plants more slowly than glufosinate, with an increase in control of susceptible plants by dicamba noted during the first 2 to 3 wk after application (Leon et al. 2014).

By 14 DAP2, all treatments containing a mixture of glufosinate plus dicamba controlled Palmer amaranth 92% to 97% (Table 3). Glufosinate rate did not influence Palmer amaranth control. Dicamba or glufosinate applied alone twice controlled Palmer amaranth less than 85%.

Glyphosate plus *S*-metolachlor plus diuron applied layby increased control in all treatments (Table 3). Following the layby application, control by dicamba alone applied twice was greater than control by glufosinate alone applied twice and similar to control by dicamba plus glufosinate applied twice. Palmer amaranth was controlled 99% by all treatments except those with glufosinate applied alone twice (87% to 91%). Similar results were noted with late-season Palmer amaranth biomass. Greater weed biomass was noted in glufosinate-only treatments compared with those containing dicamba. Biomass was similar in all treatments containing dicamba. Compared with the nontreated check, glufosinate applied alone reduced biomass 93% to 95%, while all treatments containing dicamba reduced biomass at least 99%. Cahoon et al. (2015b) reported 91% to 98% Palmer amaranth control 14 d after a layby application of diuron plus MSMA when dicamba was included in the first, second, or first and second application of glufosinate.

Cotton Growth and Injury. Cotton injury at 7 DAP1 at North Carolina environments or 10 DAP1 at Painter was 4% or less and consisted primarily of minor foliar necrosis (unpublished data). This injury was transient; no injury was observed at 14 DAP2 at any environment. Previous research has documented transient injury and rapid recovery when dicamba and glufosinate were applied to XtendFlex™ cotton (Cahoon et al. 2015b; Dixon et al. 2014).

Treatment effects were noted with cotton height at layby, height at 30 DALB, and nodes at layby (P = 0.001 for each). Cotton height and nodes at layby and cotton height at 30 DALB were less when dicamba was applied alone POST-1 compared with glufosinate plus dicamba at POST-1 (Table 4). This can be attributed to prolonged early-season

Table 4. Cotton height and nodes as affected by glufosinate and dicamba applied POST.[a,b]

Treatments						
Herbicides		Application rates		Height		Nodes at layby
POST-1	POST-2	POST-1	POST-2	At layby	30 DALB	
		g ha^{-1}		cm		no. plant^{-1}
Gluf	Gluf	590	590	59 a	85 abc	11.2 a
Gluf	Gluf	880	590	59 a	86 ab	11.2 a
Gluf + Dic	Gluf	590 + 560	590	59 a	87 a	11.3 a
Gluf + Dic	Gluf	880 + 560	590	59 a	85 abc	11.2 a
Gluf + Dic	Gluf + Dic	590 + 560	590 + 560	58 ab	87 a	11.3 a
Gluf + Dic	Gluf + Dic	880 + 560	590 + 560	57 abc	86 ab	11.2 a
Dic	Dic	560	560	51 d	79 d	10.4 b
Dic	Gluf + Dic	560	590 + 560	53 cd	80 cd	10.7 b
Dic	Gluf + Dic	560	880 + 560	54 bcd	81 bcd	10.7 b

[a] Abbreviations: DAP1, days after POST-1; DALB, days after layby; Dic, dicamba; Gluf, glufosinate.

[b] Data for height at layby, nodes at layby, and injury averaged over six environments. Data for height 30 DALB averaged over five North Carolina environments. Means within a column followed by the same letter are not different at $P \leq 0.05$ based on Fisher's protected LSD.

https://doi.org/10.1017/wet.2017.68 Published online by Cambridge University Press

competition resulting from a slower Palmer amaranth death where dicamba was applied alone compared with glufosinate alone or dicamba co-applied with glufosinate (Table 3). Cotton height and number of nodes were similar when glufosinate was applied alone or when glufosinate was co-applied with dicamba (Table 4).

Cotton Boll Production, Maturity, Lint Yield, and Fiber Quality. Herbicide treatment effects were noted for total boll production, percent open bolls, and lint yield ($P = 0.03$, 0.003, and 0.02, respectively). Boll production and lint yield were generally greatest in treatments containing glufosinate at 590 g ha^{-1} plus dicamba POST-1 (Table 5). Boll production and lint yield were similar with glufosinate at 590 g ha^{-1} POST-1 followed by glufosinate 590 g ha^{-1} POST-2 and glufosinate at 880 g ha^{-1} POST-1 followed by glufosinate at 590 g ha^{-1} POST-2. Additionally, boll production and lint yield were similar with glufosinate alone at 880 g ha^{-1} POST-1 and treatments containing glufosinate at 590 g ha^{-1} plus dicamba POST-1. Consistent with differences noted in Palmer amaranth control (Table 3), boll production and lint yield were greater in the two treatments with glufosinate at 590 g ha^{-1} plus dicamba POST-1 than in the treatment with glufosinate alone at 590 g ha^{-1} POST-1 (Table 5). Interestingly, boll production was 9% to 14% less in treatments with glufosinate at 880 g ha^{-1} plus dicamba POST-1 compared with treatments receiving glufosinate at 590 g ha^{-1} plus dicamba POST-1. Although not statistically significant, a similar trend was noted for lint yield. Numerically, lint yield was 5% to 6% less with treatments containing glufosinate at 880 g ha^{-1} plus dicamba POST-1 and those containing glufosinate at 590 g ha^{-1} plus dicamba at POST-1. These differences in boll production and lint yield could not be attributed to differences in cotton injury (Table 4).

The reduced cotton height and node number (Table 4) in treatments receiving only dicamba POST-1 was not reflected in boll production (Table 5). The cotton appeared to recover from the effects of early-season competition in treatments with only dicamba POST-1 and was able to set a similar number of bolls compared with other treatments. However, the maturity of the crop, measured as percent open bolls, was delayed in treatments receiving only dicamba POST-1. Cotton harvest occurred at least 3 wk after the open-boll counts, and visual examination indicated all harvestable bolls were open when the cotton was picked. Lint yield, but not boll production, was less with treatments that contained only dicamba at POST-1 compared with treatments containing glufosinate at 590 g ha^{-1} plus dicamba at POST-1. Boll weight was not determined, but boll weight may have been less in plots receiving only dicamba POST-1 due to early competition with slowly dying Palmer amaranth. Cotton boll production was reduced 90% to 93% in the nontreated check, and only 15% of bolls in the

Table 5. Cotton boll production, percent open bolls, and lint yield as affected by glufosinate and dicamba applied POST.[a]

Treatments						
Herbicides[b]		Application rates				
POST-1	POST-2	POST-1	POST-2	Total bolls	Open bolls	Lint yield
		g ha^{-1}		no. per 10 plants^{-1}	%	kg ha^{-1}
Gluf	Gluf	590	590	101 cd	44 a	1,000 c
Gluf	Gluf	880	590	107 abcd	44 a	1,040 abc
Gluf + Dic	Gluf	590 + 560	590	117 a	43 ab	1,110 ab
Gluf + Dic	Gluf	880 + 560	590	106 bcd	44 a	1,040 abc
Gluf + Dic	Gluf + Dic	590 + 560	590 + 560	114 ab	42 ab	1,120 a
Gluf + Dic	Gluf + Dic	880 + 560	590 + 560	98 d	48 a	1,060 abc
Dic	Dic	560	560	107 abcd	37 c	1,010 c
Dic	Gluf + Dic	560	590 + 560	109 abc	38 bc	980 c
Dic	Gluf + Dic	560	880 + 560	111 abc	36 c	1,030 c

[a] Data for lint yield averaged over six environments. Data for total bolls and open bolls averaged over the five North Carolina environments. Means within a column followed by the same letter are not different at $P \leq 0.05$ based on Fisher's protected LSD.

[b] Abbreviations: Dic, dicamba; Gluf, glufosinate.

https://doi.org/10.1017/wet.2017.68 Published online by Cambridge University Press

nontreated check were open when evaluated (unpublished data).

Herbicide treatments did not impact fiber quality. Averaged over treatments and environments, fiber micronaire, fiber strength, fiber length, and fiber length uniformity were 4.9, 27.7 g tex^{-1}, 1.07 mm, and 82.3%, respectively (unpublished data).

Results of this experiment show potential for rescue control of Palmer amaranth in Bollgard II® XtendFlex™ cotton with co-application of dicamba and glufosinate. Co-application of dicamba plus glufosinate was more effective on Palmer amaranth beyond the optimum size for treatment than either herbicide applied alone. Merchant et al. (2013) also reported improved Palmer amaranth control when glufosinate and dicamba, glufosinate and 2,4-D, or glufosinate and 2,4-dichlorophenoxy butyric acid were co-applied compared with either herbicide applied alone. In addition to improved control, a co-application would reduce selection pressure on both herbicides compared with application of herbicides individually (Behrens et al. 2007; Norsworthy et al. 2012). The layby herbicides masked some of the earlier differences in control among treatments, and there was a definite benefit from the layby application. A directed layby herbicide application is recommended in Palmer amaranth management programs (Culpepper 2016; York 2017), but most growers have abandoned the practice because directed applications are slow and tedious.

Tank mixtures of glufosinate plus dicamba formulations registered for use in Bollgard II® XtendFlex™ cotton are currently prohibited (Anonymous 2017a, 2017c), presumably because the ammonium salt formulation of glufosinate increases dicamba volatility. Research is needed to compare efficacy of sequential applications of dicamba followed by glufosinate or glufosinate followed by dicamba with that from co-applications of the two herbicides. Merchant et al. (2014) reported less control of large Palmer amaranth with 2,4-D followed by glufosinate compared with sequential application of 2,4-D plus glufosinate in nonirrigated cotton, whereas control was similar in irrigated cotton.

A weed-free check and treatments without the layby application were not included in this experiment, so it could not be determined whether the approximately 80% Palmer amaranth control at 14 DAP2 with dicamba or glufosinate alone applied twice would have been adequate to protect the crop against yield loss in the absence of the layby application. Considering the heavy infestation of Palmer amaranth at these sites, a yield reduction may have occurred in the absence of the layby application (Cahoon et al. 2014, 2015b; Culpepper et al. 2009). Enough Palmer amaranth seed would certainly have been produced to replenish the seedbank. Dicamba and glufosinate labels (Anonymous 2017b, 2017d) would allow a third POST application, and a third application would be expected to increase control. However, with its different chemistry, a layby application would be aligned with sound resistance management (Norsworthy et al. 2012).

Adverse weather conditions for herbicide application and equipment and labor constraints inevitably lead to POST herbicides being applied to weeds beyond the optimum size for treatment. However, rescue applications should be avoided when possible. Application to weeds larger than the recommended size for treatment simulates sublethal dosages (Tehranchian et al. 2017), and sublethal recurrent selection can lead to resistance in a few generations (Ashworth et al. 2016; Norsworthy 2014). Tehranchian et al. (2017) reported resistance to dicamba in Palmer amaranth after three generations of exposure to sublethal rates.

Literature Cited

Anonymous (2017a) Engenia® Herbicide Tank Mix. http://www.engeniatankmix.com. Accessed: July 14, 2017

Anonymous (2017b) Liberty® 280 SL herbicide label. http://www.cdms.net/ldat/ldUA5013.pdf. Accessed: April 17, 2017

Anonymous (2017c) XtendiMax® with VaporGrip® Technology. http://www.xtendimaxapplicationrequirements.com. Accessed: July 14, 2017

Anonymous (2017d) Xtendimax™ with VaporGrip™ Technology. Supplemental label for preemergence and postemergence use on cotton with XtendFlex Technology. http://www.cdms.net/ldat/ldDF9003.pdf. Accessed: April 17, 2017

Ashworth MB, Walsh MJ, Flower KC, Powles SB (2016) Recurrent selection with reduced 2,4- D amine doses results in the rapid evolution of 2,4-D herbicide resistance in wild radish (*Raphanus raphanistrum* L.). Pest Manag Sci 72:2091–2098

Barnett KA, Culpepper AS, York AC, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri)* control by glufosinate plus fluometuron applied postemergence to WideStrike® cotton. Weed Technol 27:291–297

Behrens MR, Mutlu N, Chakraborty S, Dumitru R, Jiang WZ, LaVallee BJ, Herman PL, Clemente TE, Weeks DP (2007) Dicamba resistance: enlarging and preserving biotechnology-based weed management strategies. Science 316:1185–1188

Bond JA, Oliver LR (2006) Comparative growth of Palmer amaranth (*Amaranthus palmeri*) accessions. Weed Sci 54:121–126

https://doi.org/10.1017/wet.2017.68 Published online by Cambridge University Press

Cahoon CW, York AC, Jordan DL, Everman WJ, Seagroves RW (2014) An alternative to multiple protoporphyrinogen oxidase inhibitor applications in no-till cotton. Weed Technol 28:58–71

Cahoon CW, York AC, Jordan DL, Everman WJ, Seagroves RW, Braswell LR, Jennings KM (2015a) Weed control in cotton by combinations of microencapsulated acetochlor and various residual herbicides applied preemergence. Weed Technol 29: 740–750

Cahoon CW, York AC, Jordan DL, Everman WJ, Seagroves RW, Culpepper AS, Eure PM (2015b) Palmer amaranth (*Amaranthus palmeri*) management in dicamba-resistant cotton. Weed Technol 29:758–770

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

Culpepper S (2016) Weed management in cotton. Pages 90–144 *in* 2016 Georgia Cotton Production Guide. Athens, GA: University of Georgia College of Agricultural and Environmental Sciences Cooperative Extension Publ. CSS-16-01. http://www.ugacotton.com/vault/file/2016-UGA-Cotton-Production-Guide.pdf. Accessed: April 17, 2017

Culpepper AS, Grey TL, Vencill WK, Kichler JM, Webster TM, Brown SM, York AC, Davis JW, Hanna WW (2006) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci 54:620–626

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: Wiley

Culpepper AS, York AC (1998) Weed management in glyphosate-tolerant cotton. J Cotton Sci 2:174–185

Culpepper AS, York AC (1999) Weed management and net returns with transgenic, herbicide-resistant, and nontransgenic cotton (*Gossypium hirsutum*). Weed Technol 13:411–420

Culpepper AS, York AC, Roberts R, Whitaker JR (2009) Weed control and crop response to glufosinate applied to 'PHY 485 WRF' cotton. Weed Technol 23:356–362

Dixon TH, Dodds DM, Copeland JD, Reynolds DZ, Samples CA, Barber LT, Main CL, Mills JA (2014) Tolerance of DGT cotton to glufosinate and dicamba. Page 161 *in* Proceedings of the 67th Annual Meeting of the Southern Weed Science Society. Birmingham, AL: Southern Weed Science Society

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

Heap I (2017) The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org. Accessed: April 17, 2017

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347–355

Leon RG, Ferrell JA, Brecke BJ (2014) Impact of exposure to 2,4-D and dicamba on peanut injury and yield. Weed Technol 28:465–470

MacRae AW, Webster TM, Sosnoskie LM, Culpepper AS, Kichler JM (2013) Cotton yield loss potential in response to length of Palmer amaranth (*Amaranthus palmeri*) interference. J Cotton Sci 17:227–232

Mehlich A (1984) Photometric determination of humic matter in soils, a proposed method. Commun Soil Sci Plant Anal 15:1417–1422

Merchant RM, Culpepper AS, Eure PM, Richburg JS, Braxton LB (2014) Salvage Palmer amaranth programs can be effective in cotton resistant to glyphosate, 2,4-D, and glufosinate. Weed Technol 28:316–322

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

Moore KJ, Dixon PM (2015) Analysis of combined experiments revisited. Agron J 107:763–771

Morgan GD, Baumann PA, Chandler JM (2001) Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. Weed Technol 15:408–412

Norsworthy JK (2014) Repeated sublethal rates of glyphosate lead to decreased sensitivity in Palmer amaranth. Crop Manag 11: 10.1094/CM-2012-0403-01-RS

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(SP1):31–62

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 2014:10.1155/2014/747810

Rowland MW, Murray DS, Verhalen LM (1999) Full-season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). Weed Sci 47:305–309

Salas RA, Burgos NR, Tranel PJ, Singh S, Glasgow L, Scott RC, Nichols RL (2016) Resistance to PPO-inhibiting herbicide in Palmer amaranth from Arkansas. Pest Manag Sci 5:864–869

Shaner DL (2000) The impact of glyphosate-tolerant crops on the use of other herbicides and on resistance management. Pest Manag Sci 56:320–326

Smith DT, Baker RV, Steele GL (2000) Palmer amaranth (*Amaranthus palmeri*) impacts on yield, harvesting, and ginning in dryland cotton (*Gossypium hirsutum*). Weed Technol 14:122–126

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 Sci 59:321–325

Steckel LE (2007) The dioecious *Amaranthus* spp.: here to stay. Weed Technol 21:567–570

Stroup WW, Littell RC (2002) Impact of variance component estimates on fixed effect inference in unbalanced mixed models. Pages 32–48 *in* Proceedings of the 14th Annual Conference on

https://doi.org/10.1017/wet.2017.68 Published online by Cambridge University Press

Applied Statistics in Agriculture. Manhattan, KS: Department of Statistics, Kansas State University

Tehranchian P, Norsworthy JK, Powles S, Bararpour MT, Bagavathiannan MV, Barber T, Scott RC (2017) Recurrent sublethal-dose selection for reduced susceptibility of Palmer amaranth (*Amaranthus palmeri*) to dicamba. Weed Sci 65: 206–212

[USDA-AMS] U.S. Department of Agriculture Agricultural Marketing Service (2001) Cotton Varieties Planted 2000 Crop. Washington, DC: USDA Publ. mp_cn 833. 10 p

[USDA-AMS] U.S. Department of Agriculture Agricultural Marketing Service (2006) Cotton Varieties Planted 2005 Crop. Washington, DC: USDA Publ. mp_cn 833. 10 p

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

Webster TM (2013) Weed survey—southern states: broadleaf crops subsection. Pages 275–287 *in* Proceedings of the 66th Annual Meeting of the Southern Weed Science Society. Houston, TX: Southern Weed Science Society

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 RG, Young BG, Matthews JL, Weller SC, Johnson WG, Jordan DL, Owen MKD, 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 seedbanks. Pest Manag Sci 67:771–780

York AC (2017) Weed management in cotton. Pages 66–112 *in* 2017 Cotton Information. Raleigh, NC: North Carolina Cooperative Extension Service Publ. AG-417. https://content.ces.ncsu.edu/cotton-information/weed-management-in-cotton. Accessed: April 17, 2017

York AC, Culpepper AS, Sosnoskie LM, Bollman S (2012) Palmer amaranth management in dicamba/glufosinate tolerant cotton. Page 98 *in* Proceedings of the 65th Annual Meeting of the Southern Weed Science Society. Charleston, SC: Southern Weed Science Society

Received April 26, 2017, and approved August 3, 2017.

Associate Editor for this paper: Daniel Stephenson, Louisana State University Agricultural Center.

https://doi.org/10.1017/wet.2017.68 Published online by Cambridge University Press