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Palmer Amaranth (*Amaranthus palmeri*) Management in Dicamba-Resistant Cotton

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Cotton growers rely heavily upon glufosinate and various residual herbicides applied preplant, PRE, and POST to control Palmer amaranth resistant to glyphosate and acetolactate synthase-inhibiting herbicides. Recently deregulated in the United States, cotton resistant to dicamba, glufosinate, and glyphosate (B2XF cotton) offers a new platform for controlling herbicide-resistant Palmer amaranth. A field experiment was conducted in North Carolina and Georgia to determine B2XF cotton tolerance to dicamba, glufosinate, and glyphosate and to compare Palmer amaranth control by dicamba to a currently used, nondicamba program in both glufosinate- and glyphosate-based systems. Treatments consisted of glyphosate or glufosinate applied early POST (EPOST) and mid-POST (MPOST) in a factorial arrangement of treatments with seven dicamba options (no dicamba, PRE, EPOST, MPOST, PRE followed by [fb] EPOST, PRE fb MPOST, and EPOST fb MPOST) and a nondicamba standard. The nondicamba standard consisted of fomesafen PRE, pyrithiobac EPOST, and acetochlor MPOST. Dicamba caused no injury when applied PRE and only minor, transient injury when applied POST. At time of EPOST application, Palmer amaranth control by dicamba or fomesafen applied PRE, in combination with acetochlor, was similar and 13 to 17% greater than acetochlor alone. Dicamba was generally more effective on Palmer amaranth applied POST rather than PRE, and two applications were usually more effective than one. In glyphosate-based systems, greater Palmer amaranth control and cotton yield were obtained with dicamba applied EPOST, MPOST, or EPOST fb MPOST compared with the standard herbicides in North Carolina. In contrast, dicamba was no more effective than the standard herbicides in the glufosinate-based systems. In Georgia, dicamba was as effective as the standard herbicides in a glyphosate-based system only when dicamba was applied EPOST fb MPOST. In glufosinate-based systems in Georgia, dicamba was as effective as standard herbicides only when dicamba was applied twice.

Nomenclature: Acetochlor; dicamba; diuron; fomesafen; glufosinate; glyphosate; MSMA; pyrithiobac; Palmer amaranth, *Amaranthus palmeri* S. Wats.; cotton, *Gossypium hirsutum* L.
Key words: Dicamba-resistant cotton, glyphosate-resistant weeds, weed management systems.

Los productores de algodón dependen mucho del uso de glufosinate y de varios herbicidas residuales aplicados pre-siembra, PRE, y POST, para el control de *Amaranthus palmeri* resistente a glyphosate y resistente a herbicidas inhibidores de acetolactate synthase. Recientemente desregulado en los Estados Unidos, el algodón resistente a dicamba, glufosinate, y glyphosate (algodón B2XF) ofrece una nueva plataforma para el control de *A. palmeri* resistente a herbicidas. En North Carolina y Georgia, se realizó un experimento de campo para determinar la tolerancia de B2XF a dicamba, glufosinate, y glyphosate y para comparar el control de *A. palmeri* con dicamba con un programa actualmente usado (sin dicamba) en sistemas basados en glufosinate y glyphosate. Los tratamientos de glyphosate y glufosinate aplicados POST temprano (EPOST) y POST medio (MPOST) en un arreglo factorial de tratamientos con siete opciones de dicamba (sin dicamba, PRE, EPOST, MPOST, PRE seguido de [fb] EPOST, PRE fb MPOST, y EPOST fb MPOST) y un estándar sin dicamba. El estándar sin dicamba consistió en fomesafen PRE, pyrithiobac EPOST, y acetochlor MPOST. Dicamba no causó ningún daño cuando se aplicó PRE y solamente un daño menor y temporal cuando se aplicó POST. Al momento de la aplicación EPOST, el control de *A. palmeri* con dicamba o fomesafen aplicados PRE, en combinación con acetochlor fue similar, y fue de 13 a 17% mayor al de acetochlor solo. Dicamba fue generalmente más efectivo sobre *A. palmeri* aplicado POST que PRE, y dos aplicaciones fueron usualmente más efectivas que una. En sistemas basados en glyphosate, un mayor control de *A. palmeri* y mayor rendimiento del algodón fueron obtenidos con dicamba aplicado EPOST, MPOST, o

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EPOST fb MPOST al compararse con los herbicidas estándar en North Carolina. En contraste, dicamba no fue más efectivo que los herbicidas estándar en sistemas basados en glufosinate. En Georgia, dicamba fue tan efectivo como los herbicidas estándar en un sistema basado en glyphosate solamente cuando dicamba fue aplicado EPOST fb MPOST. En sistemas basados en glufosinate, en Georgia, dicamba fue tan efectivo como los herbicidas estándar solamente cuando dicamba se aplicó dos veces.

Palmer amaranth is the most troublesome weed in cotton and other agronomic crops in the southern United States (Webster 2013). The biology of this weed, its impact on cotton yield, and the difficulty of control in cotton were reviewed by Culpepper et al. (2010). Rapid growth, large plant stature, and drought tolerance mechanisms give Palmer amaranth a competitive advantage over cotton (Bond and Oliver 2006; Horak and Loughin 2000; Place et al. 2008; Sellers et al. 2003; Wright et al. 1999). Palmer amaranth can dramatically reduce cotton yield, with yield reductions up to 92% with eight weeds m^{-1} of row (MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999). It can also interfere with or prevent mechanical harvest (Morgan et al. 2001; Smith et al. 2000). Prolific seed production allows dense populations to build up quickly from minor infestations (Bensch et al. 2003; Burke et al. 2007; Inman et al. 2014; MacRae et al. 2013; Norsworthy et al. 2014). Continued plant emergence and seed production throughout the season enable the weed to replenish seed banks if season-long control is not obtained (Jha and Norsworthy 2009; Keely et al. 1987; MacRae et al. 2013).

Glyphosate-resistant (GR) cotton cultivars, commercially released in 1997, revolutionized weed management in cotton (Culpepper and York 1998, 1999; Faircloth et al. 2001; Gianessi 2008), and the technology was quickly adopted by growers. Ninety-eight percent of cotton in Arkansas and Georgia and greater than 99% in other states in the Southeast and mid-South regions of the U.S. Cotton Belt were planted to cultivars resistant to glyphosate or glyphosate and glufosinate in 2013 (USDA-AMS 2014).

Glyphosate once provided excellent control of Palmer amaranth (Bond et al. 2006; Corbett et al. 2004; Culpepper and York 1998, 1999; Scott et al. 2002) and cotton growers relied heavily on glyphosate while reducing use of other herbicides (Givens et al. 2009; Sosnoskie and Culpepper 2014; Wilson et al. 2011). Unfortunately, excessive reliance on glyphosate and the reduction in use of other herbicides led to selection for resistant biotypes. Resistance to glyphosate has now been confirmed in 32 and 14 weed species globally and in the United States, respectively (Heap 2015). The first confirmation of resistance to glyphosate in an *Amaranthus* species occurred with Palmer amaranth in Georgia in 2005 (Culpepper et al. 2006). By 2014, GR Palmer amaranth had been confirmed in 24 states in the United States (Heap 2015). Multiple resistance to glyphosate and acetolactate synthase (ALS)-inhibiting herbicides has also been documented (Heap 2015; Nandula et al. 2012; Poirier et al. 2014; Sosnoskie et al. 2011).

Increasing infestations of glyphosate- and ALS-resistant Palmer amaranth in cotton has forced producers to utilize herbicides with alternative modes of action in their management systems (Sosnoskie and Culpepper 2014). Of particular note is the increase in use of protoporphyrinogen oxidase (PPO)-inhibiting herbicides and glufosinate for management of GR Palmer amaranth by producers. Palmer amaranth can be controlled in systems utilizing glufosinate and PPO-inhibiting herbicides such as flumioxazin and fomesafen (Everman et al. 2009; Gardner et al. 2006; Whitaker et al. 2011a,b), but there is increasing concern over the potential to select for resistance to these herbicides (Cahoon et al. 2014; Jalaludin et al. 2015; York 2015).

Transgenic cotton resistant to dicamba and glufosinate (event MON88701) was recently deregulated in the United States (USDA-APHIS 2015). This cotton was genetically engineered for resistance to dicamba through insertion of the dicamba monooxygenase (*dmo*) gene from *Stenotrophomonas maltophilia* that expresses a monooxygenase enzyme that rapidly demethylates dicamba to the herbicidally inactive compounds 3,6-dichlorosalicylic acid and formaldehyde, thereby conferring tolerance to dicamba (Behrens et al. 2007). MON88701 cotton also contains a bialaphos resistance (*bar*) gene (from *Streptomyces hygroscopicus*) that expresses the phosphinothricin *N*-acetyltransferase protein to confer tolerance to glufosinate (Mannion and Malven 2013). Cultivars resistant to dicamba, glufosinate, glyphosate, and lepidopteran insects (MON88701 by MON88913 by MON15985; brand name Bollgard II® XtendFlex™, hereafter referred to B2XF) have been developed (ISAAA 2015) and commercial sales began in 2015 (Anonymous 2015).

Combinations of glyphosate plus dicamba applied preplant have effectively controlled GR biotypes of horseweed (*Conyza canadensis* (L.) Cronq.) (Eubank et al. 2008; Steckel et al. 2006). Combinations of glyphosate plus dicamba applied POST in dicamba-resistant soybean (*Glycine max* (L.) Merr.) also were more effective on GR horseweed, giant ragweed (*Ambrosia trifida* L.), common waterhemp (*Amaranthus rudis* Saur.), and Palmer amaranth than glyphosate alone (Byker et al. 2013; Johnson et al. 2010; Vink et al. 2012). Dicamba, applied to B2XF cotton, may give cotton growers a new tool to control GR weeds and to slow or prevent selection for other biotypes resistant to glyphosate or glufosinate. In the current study, our objectives were to evaluate tolerance of B2XF cotton to dicamba, to determine the effect of dicamba applied PRE and POST on Palmer amaranth control in glyphosate- and glufosinate-based systems, and to compare Palmer amaranth control in systems that included dicamba with that of currently used, nondicamba systems.

Materials and Methods

Experiments were conducted on private farms near Mount Olive, NC (35.20°N, 77.97°W) during 2013 and 2014 and near Oglethorpe, GA (32.42°N, 84.13°W) during 2013. Fields at each location were naturally infested with Palmer amaranth at densities greater than 100 plants m^{-2}. Soil in North Carolina was a Wagram loamy sand (loamy, kaolinitic, thermic Arenic Kandiudults) with 0.46 and 0.51% humic matter and pH 5.6 and 5.4 in 2013 and 2014, respectively. Humic matter was determined photometrically according to Mehlich (1984). Soil in Georgia was a Dothan loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with 1.9% organic matter (determined by loss on ignition according to Ben-Dor and Banin [1989]) and pH 6.3.

An experimental B2XF cotton cultivar from Monsanto Company (St. Louis, MO) was planted at approximately 14 seed m^{-1} of row at each site in early May 2012 and 2013. Cotton was seeded using a strip-tillage system (Meijer and Edmisten 2015) in a desiccated wheat (*Triticum aestivum* L.) cover crop in North Carolina. All plots received a preplant application of glyphosate at 1,260 g ae ha^{-1} plus 2,4-D at 530 g ae ha^{-1} approximately 3 to 4 wk before planting. Paraquat at 840 g ai ha^{-1} was applied at planting for control on any remaining vegetation. Cotton in Georgia was seeded in a conventionally prepared seedbed. The experimental design was a randomized complete block with treatments replicated four times in Georgia and North Carolina in 2013 and three times in North Carolina in 2014. Plot size in North Carolina was four rows by 9 m, with row spacing of 97 cm. Plot size in Georgia was four rows by 8 m, with row spacing of 91 cm.

Treatments were arranged in a factorial arrangement of two base herbicide systems by eight dicamba/nondicamba programs plus a nontreated check. Herbicide sources and application rates are listed in Table 1. Base herbicide systems were glufosinate and glyphosate applied to 2- to 3-leaf cotton at 18 to 23 d after planting (early POST [EPOST]) followed by (fb) a second application 18 to 22 d later to 8- to 10-leaf cotton (mid-POST [MPOST]). Dicamba options included no dicamba and dicamba applied PRE, EPOST, MPOST, PRE fb EPOST, PRE fb MPOST, and EPOST fb MPOST. The nondicamba option, a currently used standard program, included fomesafen applied PRE, pyrithiobac applied EPOST, and acetochlor applied MPOST. All dicamba, pyrithiobac, and acetochlor POST treatments were coapplied with glyphosate or glufosinate. Palmer amaranth was 10 cm or less in height at EPOST. Palmer amaranth at MPOST ranged from 10 to 40 cm, depending upon previous herbicide applications. All treatments, except the nontreated, included acetochlor applied PRE and diuron plus MSMA POST-directed to cotton 41 to 58 cm in height at 14 to 18 d after MPOST application. PRE and POST herbicides were applied using CO_2-pressurized backpack sprayers equipped with flat-fan nozzles (AIXR 11002 TeeJet® Air Induction XR flat-spray nozzles, TeeJet Technologies, Wheaton, IL) delivering 140 L ha^{-1} at 165 kPa. Layby herbicides were applied with a single flood nozzle (TK-VS2 FloodJet® wide angle flat-spray nozzle, TeeJet Technologies) per row middle delivering 140 L ha^{-1} at 210 kPa.

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Table 1. Herbicides and application rates and timings.[a]

Year	Herbicide common names	Brand names or designations	Application times	Application rates	Manufacturer
2013	Dicamba, DGA salt	MON 119096	PRE, EPOST, MPOST	560 g ae ha^{-1}	Monsanto Company, St. Louis, MO, http://www.monsanto.com
2013	Glyphosate, MEA salt + dicamba DGA salt	MON 76832	EPOST, MPOST	1,120 + 560 g ae ha^{-1}	Monsanto Company
2014	Glyphosate, K salt	Roundup PowerMAX®	EPOST, MPOST	1,260 g ae ha^{-1}	Monsanto Company
2014	Dicamba, DGA salt	Clarity®	PRE, EPOST, MPOST	560 g ae ha^{-1}	BASF Ag Products, Research Triangle Park, NC, http://www.basf.com
2013, 2014	Acetochlor	Warrant®	PRE, EPOST, MPOST	1,260 g ai ha^{-1}	Monsanto Company
2013, 2014	Diuron	Direx® 4L	Layby	1,120 g ai ha^{-1}	ADAMA Agriculture Solutions, Raleigh, NC, http://www.adama.com
2013, 2014	Fomesafen	Reflex®	PRE	200 g ai ha^{-1}	Syngenta Crop Protection, Greensboro, NC, http://www.syngenta.com
2013, 2014	Glufosinate	Liberty® 280SL	EPOST, MPOST	560 g ai ha^{-1}	Bayer CropScience, Research Triangle Park, NC, http://www.cropscience.bayer.com
2013, 2014	Glyphosate, K salt	Roundup PowerMAX®	Preplant	1,260 g ae ha^{-1}	Monsanto Company
2013, 2014	MSMA	MSMA 6.6	Layby	1,850 g ai ha^{-1}	Drexel Chemical Company, Memphis, TN, http://www.drexchem.com
2013, 2014	Paraquat	Parazone® 3SL	PRE	840 g ha^{-1}	ADAMA Agriculture Solutions, Raleigh, NC, http://www.adama.com
2013, 2014	Pyrithiobac	Staple® LX	EPOST	56 g ai ha^{-1}	DuPont Crop Protection, Wilmington, DE, http://www.dupont.com
2013, 2014	2,4-D	Weedar® 64	Preplant	530 g ae ha^{-1}	Nufarm Agricultural Products, Alsip, IL, http://www.nufarm.com

[a] Abbreviations: DGA, diglycolamine; MEA, monoethanolamine; EPOST, early POST, to 2- to 3-leaf cotton; MPOST, mid-POST, to 8- to 10-leaf cotton.

Palmer amaranth control and cotton injury were estimated visually according to Frans et al. (1986). Control was recorded at time of EPOST (18 to 23 d after planting), at time of layby (14 to 18 d after MPOST), 14 d after layby, and late in the season (early to mid-September, before defoliation). Cotton injury was determined at time of EPOST, 7 d after EPOST, and 14 d after MPOST. Late in the season, Palmer amaranth density in each plot was determined by counting the number of plants from 1 m^2 in the nontreated and from three row middles (22 to 28 m^2) in treated plots. All treated plots were mechanically harvested in mid-October to mid-November. The nontreated plots were too weedy to harvest and yields were assumed to be zero. Data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS (version 9.3; SAS Institute Inc., Cary, NC). Herbicide treatments and locations were fixed effects and replications were treated as random. Means were separated using Fisher's Protected LSD at $P \leq 0.05$. Data for nontreated were not included in analyses. To evaluate weed control and cotton injury by PRE herbicides before EPOST application, data for treatments receiving the same PRE herbicides were combined. Dunnett's procedure (Dunnett 1955) was utilized to compare Palmer amaranth densities in the nontreated with all other treatments.

Results and Discussion

A location-by-PRE herbicide interaction was observed for Palmer amaranth control before EPOST application, and a base herbicide system-by-program-by-location interaction was observed at later evaluations. However, data for the two North Carolina locations could be combined.

Cotton Injury. No injury was observed with acetochlor, acetochlor plus dicamba, or acetochlor plus fomesafen PRE when evaluated 18 to 23 d after application (DAA) (data not shown). Lack of B2XF cotton injury from dicamba applied PRE has been observed by others (Dodds et al. 2012; Reynolds et al. 2013; York et al. 2015).

Glufosinate alone or coapplied with dicamba injured cotton 3 to 6% in North Carolina and 9 to 14% in Georgia 7 d after EPOST (Table 2). This injury appeared primarily as foliar necrosis. Glyphosate alone injured cotton 2% or less 7 d after EPOST application. Dicamba coapplied with glyphosate increased injury 1 to 6% in North Carolina and 9 to 13% in Georgia. Injury by glufosinate and dicamba coapplied with glufosinate or glyphosate was transient, with no injury observed 14 d after EPOST and MPOST in North Carolina and 5% or less and no injury 14 d after EPOST and MPOST, respectively, in Georgia. Results from this study are similar to those reported by Dixon et al. (2014), where dicamba and glyphosate plus dicamba, each applied at 1,120 g ha^{-1} to four-leaf B2XF cotton, caused 7 and 13% injury, respectively, 7 DAA. In that study, injury was also transitory and cotton yield was unaffected. Similarly, in other North Carolina experiments, glyphosate plus dicamba at 1,120 plus 560 g ha^{-1} and 4,480 plus 2,240 g ha^{-1} (using MON 76832) applied sequentially to 5-, 9-, and 12-leaf B2XF cotton caused 3 to 11% and 15 to 27% necrosis, respectively, 7 d after each application but yields were unaffected (A.C. York, unpublished data). In another study, glyphosate plus dicamba at 2,240 plus 1,120 g ha^{-1} caused 18, 4, and 0% necrosis at 3, 14, and 27 DAA to four-leaf B2XF cotton, respectively, but yield was unaffected (A.C. York, unpublished data). Glufosinate at 655 g ha^{-1} plus dicamba at 560 g ha^{-1} applied to eight-leaf B2XF cotton caused 5 and 0% necrosis at 3 and 16 DAA, respectively, and yield was unaffected (A.C. York, unpublished data).

Three to 5% injury in North Carolina and 10 to 17% injury in Georgia was noted with the nondicamba standard herbicides 7 d after EPOST (Table 2). Cotton quickly recovered, with no injury evident at 14 d after EPOST in North Carolina and 3% or less in Georgia. The nondicamba standards were the only treatments with injury at 14 d after MPOST. This injury was due to foliar necrosis caused by acetochlor applied MPOST.

Palmer Amaranth Control and Cotton Yield. Residual control of Palmer amaranth by dicamba was observed before EPOST herbicide application (Table 3). Compared with acetochlor alone, acetochlor plus dicamba PRE increased control 13 and 17% in North Carolina and Georgia, respectively. Control after acetochlor plus dicamba and acetochlor plus fomesafen PRE was similar in both states. Palmer amaranth control after dicamba PRE has been reported by others (Hayes et al. 2014; Sanders et al. 2013; York et al. 2015). The first rainfall after PRE application, totaling 0.9, 2.2, and 2.3 cm, was

Table 2. Cotton injury with glufosinate- and glyphosate-based systems plus dicamba compared with a nondicamba standard treatment containing fomesafen, pyrithiobac, and acetochlor.[a]

Herbicides and application timings[b,c]			North Carolina			Georgia		
			7 d after	14 d after	14 d after	7 d after	14 d after	14 d after
PRE	EPOST	MPOST	EPOST	EPOST	MPOST	EPOST	EPOST	MPOST
			%					
Acet	Gluf	Gluf	3 de	0 a	0 c	12 bcd	1 bc	0 b
Acet + dicamba	Gluf	Gluf	6 ab	0 a	0 c	9 d	1 bc	0 b
Acet	Gluf + dicamba	Gluf	6 ab	0 a	0 c	14 ab	2 abc	0 b
Acet	Gluf	Gluf + dicamba	5 bc	0 a	0 c	12 bcd	1 bc	0 b
Acet + dicamba	Gluf + dicamba	Gluf	4 cd	0 a	0 c	14 ab	3 abc	0 b
Acet + dicamba	Gluf	Gluf + dicamba	3 de	0 a	0 c	12 bcd	4 ab	0 b
Acet	Gluf + dicamba	Gluf + dicamba	5 bc	0 a	0 c	12 bcd	1 bc	0 b
Acet + fome	Gluf + pyri	Gluf + acet	5 bc	0 a	4 a	17 a	3 abc	18 a
Acet	Glyph	Glyph	1 f	0 a	0 c	0 e	1 bc	0 b
Acet + dicamba	Glyph	Glyph	1 f	0 a	0 c	0 e	1 bc	0 b
Acet	Glyph + dicamba	Glyph	5 bc	0 a	0 c	9 d	2 bc	0 b
Acet	Glyph	Glyph + dicamba	2 ef	0 a	0 c	0 e	0 c	0 b
Acet + dicamba	Glyph + dicamba	Glyph	7 a	0 a	0 c	13 bc	2 abc	0 b
Acet + dicamba	Glyph	Glyph + dicamba	1 f	0 a	0 c	0 e	2 abc	0 b
Acet	Glyph + dicamba	Glyph + dicamba	5 bc	0 a	0 c	11 bcd	5 a	0 b
Acet + fome	Glyph + pyri	Glyph + acet	3 de	0 a	3 b	10 cd	0 c	18 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$. Data for North Carolina are averaged over two locations.

[b] Abbreviations: Acet, acetochlor; fome, fomesafen; gluf, glufosinate; glyph, glyphosate; pyri, pyrithiobac; EPOST, early POST, to 2- to 3-leaf cotton; MPOST, mid-POST, to 8- to 10-leaf cotton.

[c] Acetochlor, dicamba, fomesafen, glufosinate, glyphosate, dicamba, and pyrithiobac applied at 1,260, 560, 200, 560, 1,260, and 56 g ha^{-1}, respectively. All treatments included diuron at 1,120 g ha^{-1} plus MSMA at 1,850 g ha^{-1} applied POST-directed.

Table 3. Palmer amaranth control with PRE herbicides 18 to 23 d after planting.[a]

PRE herbicides[b]	North Carolina	Georgia
	—%—	
Acetochlor	67 b	82 b
Acetochlor + dicamba	80 a	99 a
Acetochlor + fomesafen	73 ab	99 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$. Data for North Carolina are averaged over two locations.

[b] Acetochlor, dicamba, and fomesafen applied at 1,260, 560, and 200 g ha^{-1}, respectively.

received at 8, 10, and 12 d in Georgia and North Carolina in 2013, and North Carolina in 2014, respectively. In other North Carolina and Georgia experiments, greater residual control by dicamba was observed when rainfall in the first 10 to 12 DAA was limited (A.C. York and A.S. Culpepper, unpublished data). Similar results were reported by Edwards et al. (2013) and Steckel et al. (2013). Dicamba has a short soil half-life due to microbial degradation (Krzyszowska et al. 1994; Smith 1973, 1974; Smith and Cullimore 1975; Voos and Groffman 1997) and persistence is shorter under warm and moist conditions. Smith (1973) reported that 95% of applied dicamba was degraded in 2 wk in a moist sandy loam soil. Additionally, dicamba is highly mobile in soil (Grover 1977; Helling 1971; Krzyszowska et al. 1994). Under dry conditions, where microbial degradation would be less rapid and leaching would not occur, more dicamba would be available to control shallow-germinating weeds such as Palmer amaranth.

On the basis of the response to glyphosate applied alone in these experiments and previous experiments in the same fields, an estimated 40 and 60% of the Palmer amaranth population was resistant to glyphosate in North Carolina and Georgia, respectively. In both states, glufosinate was more effective than glyphosate for Palmer amaranth control, an expected observation since a portion of the Palmer amaranth was resistant to glyphosate (Tables 4 and 5). Glyphosate applied EPOST fb MPOST, after acetochlor PRE, controlled Palmer amaranth 54% before layby compared with 75% control by glufosinate applied EPOST fb MPOST in each state. At subsequent evaluations in both states, glufosinate POST controlled Palmer amaranth 28 to 67% greater than glyphosate. Late-season control in North Carolina was 48 or 80% after only glyphosate or glufosinate POST, respectively, whereas the same treatments provided 5 and 72% control in Georgia, respectively. Late-season Palmer amaranth densities were four to six times greater in both states after treatments containing only glyphosate POST compared with glufosinate only POST (Table 4 and 5). Similarly, cotton yield after systems containing glyphosate only POST were 60 and 14% of yields recorded after glufosinate-only POST systems in North Carolina and Georgia, respectively.

In North Carolina, dicamba PRE increased Palmer amaranth control 10% at 14 d after layby in glyphosate-based systems (Table 4). However, dicamba was more effective when applied POST. Compared with glyphosate alone, dicamba applied EPOST or MPOST increased Palmer amaranth control 29, 31 to 37, and 33 to 40% at layby, 14 d after layby, and late season, respectively. Dicamba applied sequentially was more effective than dicamba applied only EPOST in North Carolina (Table 4). The addition of dicamba PRE did not provide an increase in Palmer amaranth control, regardless of the POST application timing of dicamba. Dicamba applied EPOST, MPOST, or EPOST fb MPOST reduced late-season Palmer amaranth density and increased cotton yield compared with glyphosate-only POST systems and the nondicamba standard treatment in North Carolina (Table 4).

Overall, the increase in Palmer amaranth control observed with dicamba in a glufosinate-based system was not as substantial as when dicamba was added to a glyphosate-based system in North Carolina (Table 4). This likely occurred because glufosinate alone was more effective than glyphosate alone for Palmer amaranth control, which is similar to the results of York et al. (2015). No dicamba-containing treatment reduced late-season Palmer amaranth density or increased cotton yield compared with glufosinate-only treatments (Table 4). Compared with glufosinate-only treatments, dicamba applied PRE or EPOST did not increase Palmer amaranth control at layby or at later evaluations. However, dicamba MPOST increased control 16, 12, and 13% at layby, 14 d after layby, and late season, respectively, compared with glufosinate-only treatments. Dicamba applied EPOST fb MPOST provided similar Palmer amaranth control to

Table 4. Palmer amaranth control, Palmer amaranth density, and seed cotton yield with glufosinate- and glyphosate-based systems plus dicamba compared with a nondicamba standard treatment containing fomesafen, pyrithiobac, and acetochlor in North Carolina.[a]

Herbicides and application timings[b,c]			Palmer amaranth control			Palmer amaranth density[d]	Seed cotton yield
PRE	EPOST	MPOST	At layby	14 d after layby	Late season		
			—————%—————			Plants ha^{-1} × 1,000	kg ha^{-1}
Acet	Gluf	Gluf	75 de	84 d	80 e	5.6 b	2,930 abc
Acet + dicamba	Gluf	Gluf	81 cd	89 bcd	82 de	3.5 b	3,000 ab
Acet	Gluf + dicamba	Gluf	84 bcd	91 a-d	83 cde	2.2 b	2,900 bc
Acet	Gluf	Gluf + dicamba	91 abc	96 abc	93 a-d	1.5 b	3,010 ab
Acet + dicamba	Gluf + dicamba	Gluf	93 ab	98 ab	98 a	0.4 b	3,320 ab
Acet + dicamba	Gluf	Gluf + dicamba	93 ab	98 ab	95 ab	1.3 b	3,440 ab
Acet	Gluf + dicamba	Gluf + dicamba	92 ab	96 abc	94 abc	0.6 b	3,180 ab
Acet + fome	Gluf + pyri	Gluf + acet	90 abc	90 a-d	86 b-e	2.0 b	3,000 ab
Acet	Glyph	Glyph	54 g	56 f	48 f	22.9 a	1,740 d
Acet + dicamba	Glyph	Glyph	64 fg	66 e	59 f	16.9 a	2,130 d
Acet	Glyph + dicamba	Glyph	83 bcd	87 cd	81 e	4.3 b	3,110 ab
Acet	Glyph	Glyph + dicamba	83 bcd	93 a-d	88 a-e	2.8 b	3,170 ab
Acet + dicamba	Glyph + dicamba	Glyph	96 abc	91 a-d	86 b-e	2.3 b	3,120 ab
Acet + dicamba	Glyph	Glyph + dicamba	85 a-d	95 abc	92 a-e	1.6 b	3,230 ab
Acet	Glyph + dicamba	Glyph + dicamba	95 a	99 a	99 a	0.2 b	3,600 a
Acet + fome	glyph + pyri	Glyph + acet	65 ef	61 ef	57 f	22.6 a	2,280 cd

[a] Data are averaged over two locations. Means within a column followed by the same letter are not different according to Fisher's protected LSD test at $P \leq 0.05$.

[b] Abbreviations: Acet, acetochlor; fome, fomesafen; gluf, glufosinate; glyph, glyphosate; pyri, pyrithiobac; EPOST, early POST, to 2- to 3-leaf cotton; MPOST, mid-POST, to 8- to 10-leaf cotton.

[c] Acetochlor, dicamba, fomesafen, glufosinate, glyphosate, dicamba, and pyrithiobac applied at 1,260, 560, 200, 560, 1,260, and 56 g ha^{-1}, respectively. All treatments included diuron at 1,120 g ha^{-1} plus MSMA at 1,850 g ha^{-1} applied POST-directed, respectively..

[d] Palmer amaranth density recorded late in the season. Density in nontreated check was 915,300 plants ha^{-1}. Density of check differed from all herbicide treatments according to Dunnett's procedure at $P \leq 0.05$.

dicamba applied EPOST or MPOST only. Systems that included dicamba MPOST, PRE fb EPOST or MPOST, or EPOST fb MPOST controlled Palmer amaranth at least 93% compared with 80% control by glufosinate-only treatments.

In contrast to results from North Carolina, where little to no improvement in Palmer amaranth control was noted at layby or later after dicamba PRE, dicamba PRE in Georgia increased Palmer amaranth control throughout the season in both the glyphosate- and glufosinate-based systems (Table 5). Dicamba PRE increased control 9, 23, and 33% at layby, 14 d after layby, and late season, respectively, compared with glyphosate-only treatments and 11 and 14% compared with glufosinate-only treatments at 14 d after layby and late season, respectively. Dicamba PRE also reduced Palmer amaranth density in both systems compared with glyphosate- and glufosinate-only treatments, but did not affect cotton yield.

Dicamba applied POST, regardless of the time or number of applications, increased Palmer amaranth control, reduced late-season Palmer amaranth density, and increased cotton yield in both the glyphosate- and glufosinate-based systems in Georgia (Table 5). Dicamba EPOST controlled Palmer amaranth 9% greater than dicamba MPOST in the glyphosate-based system at layby, but otherwise dicamba was similarly effective when applied EPOST or MPOST in both the glyphosate- and glufosinate-based systems. However, sequential dicamba POST applications were 11 to 20, 20 to 25, and 16 to 23% more effective than one dicamba POST application at layby, 14 d after layby, and late season, respectively. Palmer amaranth control and cotton yield were similar after dicamba applied EPOST fb MPOST and dicamba PRE fb dicamba

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Table 5. Palmer amaranth control, Palmer amaranth density, and seed cotton yield with glufosinate- and glyphosate-based systems plus dicamba compared with a nondicamba standard treatment containing fomesafen, pyrithiobac, and acetochlor in Georgia.[a]

Herbicides and application timings[b,c]			Palmer amaranth control				
PRE	EPOST	MPOST	At layby	14 d after layby	Late season	Palmer amaranth density[d]	Seed cotton yield
			%			Plants ha^{-1} × 1,000	kg ha^{-1}
Acet	Gluf	Gluf	75 ef	79 de	72 d	38.0 de	1,530 ef
Acet + dicamba	Gluf	Gluf	81 cde	90 c	86 bc	20.1 fg	2,090 de
Acet	Gluf + dicamba	Gluf	85 bcd	92 bc	85 bc	15.1 fgh	2,570 cd
Acet	Gluf	Gluf + dicamba	79 de	91 c	89 b	23.7 ef	3,050 abc
Acet + dicamba	Gluf + dicamba	Gluf	100 a	100 a	100 a	0 h	3,090 abc
Acet + dicamba	Gluf	Gluf + dicamba	89 b	96 abc	99 a	0.7 h	3,320 a
Acet	Gluf + dicamba	Gluf + dicamba	87 bc	98 ab	100 a	0 h	3,120 abc
Acet + fome	Gluf + pyri	Gluf + acet	84 bcd	93 bc	99 a	1.8 h	3,340 a
Acet	Glyph	Glyph	54 i	35 h	5 f	241.7 a	210 g
Acet + dicamba	Glyph	Glyph	63 gh	58 g	38 e	106.2 b	330 g
Acet	Glyph + dicamba	Glyph	70 fg	75 ef	77 cd	58.5 c	1,690 ef
Acet	Glyph	Glyph + dicamba	61 hi	70 f	70 d	47.7 cd	1,640 ef
Acet + dicamba	Glyph + dicamba	Glyph	66 gh	75 ef	74 d	63.1 c	1,400 ef
Acet + dicamba	Glyph	Glyph + dicamba	76 ef	83 d	86 bc	29.1 ef	1,720 ef
Acet	Glyph + dicamba	Glyph + dicamba	81 cde	95 abc	93 ab	20.4 fg	2,680 bc
Acet + fome	Glyph + pyri	Glyph + acet	80 cde	93 bc	88 b	5.4 gh	3,180 ab

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[b] Abbreviations: Acet, acetochlor; fome, fomesafen; gluf, glufosinate; glyph, glyphosate; pyri, pyrithiobac; EPOST, early POST, to 2- to 3-leaf cotton; MPOST, mid-POST, to 8- to 10-leaf cotton.

[c] Acetochlor, dicamba, fomesafen, glufosinate, glyphosate, dicamba, and pyrithiobac applied at 1,260, 560, 200, 560, 1,260, and 56 g ha^{-1}, respectively. All treatments included diuron at 1,120 g ha^{-1} plus MSMA at 1,850 g ha^{-1} applied POST-directed, respectively.

[d] Palmer amaranth density recorded late in the season. Density of nontreated check was 1,009,200 plants ha^{-1}. Density of check differed from all herbicide treatments according to Dunnett's procedure at $P \leq 0.05$.

MPOST in glufosinate- and glyphosate-based systems. However, cotton yield was only greater than the glufosinate- or glyphosate-only treatments after dicamba EPOST fb MPOST in the glyphosate-based system. In glyphosate-based systems, Palmer amaranth control and cotton yield were greater after dicamba applied sequentially POST than dicamba PRE fb EPOST. However, excellent control was obtained with both of the aforementioned treatments and yields were similar in the glufosinate-based system in Georgia.

Palmer amaranth control in North Carolina using standard herbicides (fomesafen PRE, pyrithiobac EPOST, acetochlor MPOST) applied in the glufosinate-based system was much greater than control by the standard herbicides in the glyphosate-based system. Standard herbicides in the glufosinate-based system controlled Palmer amaranth 90, 90, and 86% at layby, 14 d after layby, and late season, respectively, compared with 65, 61, and 57% control at the same evaluation times in the glyphosate-based system (Table 4). In both base herbicide systems, the standard herbicides were more effective than glyphosate- or glufosinate-only treatments at layby, but similar at later evaluations. In Georgia, the standard herbicides improved control at all evaluations in both the glyphosate- and glufosinate-based systems compared with glyphosate- and glufosinate-only treatments (Table 5). Compared with the same treatments, the standard herbicides increased control 9, 14, and 27% at layby, 14 d after layby, and late season, respectively, in the glufosinate-based system and 26, 58, and 83% at the same evaluation intervals in the glyphosate-based system. Control by the two standard programs in Georgia differed only at the late-season evaluation interval, where standard herbicides in the glufosinate-based system controlled Palmer amaranth 99% compared with 88% in the glyphosate-based system. Palmer amaranth density and cotton yield were similar with the standard herbicides in both base herbicide systems. In North Carolina, in contrast to results in Georgia, greater Palmer amaranth control, fewer late-season plants, and greater cotton yield were noted with standard herbicides in the glufosinate-based program than in the glyphosate-based system (Table 4). Differences between states in Palmer amaranth control with the standard herbicides in the glyphosate-based program are likely due to differences in ALS resistance in the Palmer amaranth populations. Previous experience in the fields suggests that a relatively high percentage of the population in North Carolina consisted of an ALS-resistant biotype, whereas little ALS resistance was present in Georgia.

A key question in this experiment was how Palmer amaranth control and cotton yield would compare with dicamba-containing systems and systems with standard herbicides. In glyphosate-based systems in North Carolina, dicamba applied EPOST, MPOST, or EPOST fb MPOST provided greater Palmer amaranth control, fewer Palmer amaranth plants late in the season, and greater cotton yields than the standard herbicides (Table 4). In contrast, in glufosinate-based systems, dicamba was no more effective than the standard herbicides. However, neither dicamba nor the standard herbicides reduced late-season weed density or increased cotton yield relative to glufosinate alone. On the basis of late-season Palmer amaranth control, density, and cotton yield in Georgia, dicamba was as effective as the standard herbicides in a glyphosate-based program only when dicamba was applied EPOST fb MPOST (Table 5). All other dicamba- and glyphosate-containing treatments were less effective than glyphosate applied with the standard herbicides. In glufosinate-based systems, dicamba was as effective as standard herbicides only when dicamba was applied twice (PRE fb EPOST, PRE fb MPOST, or EPOST fb MPOST).

The B2XF cotton in this study displayed excellent tolerance of glufosinate, glyphosate, and dicamba. Although minor injury was observed with dicamba and glufosinate applied POST, the injury was transitory and did not affect cotton yield. Dixon et al. (2014) reported similar observations. Our results demonstrate that dicamba can be beneficial in managing GR Palmer amaranth. Residual control from dicamba applied PRE was observed under limited rainfall after application. However, dicamba was generally more beneficial when applied POST and two POST applications were more effective than one application. Most of the Palmer amaranth in the southeastern United States is resistant to glyphosate, and cotton growers predominately utilize glufosinate plus residual herbicides applied PRE and POST for weed control. Our results demonstrated similar Palmer amaranth control and cotton yield with dicamba plus glufosinate and standard residual herbicides (acetochlor, fomesafen, pyrithiobac) plus glufosinate. Inconsistent results were noted in glyphosate-based systems. In Georgia, dicamba was generally less effective than the standard herbicides in a glyphosate-based system. Dicamba was similar to standard herbicides only when dicamba was applied sequentially POST. In contrast, systems containing dicamba applied POST once or twice were superior to a system with standard herbicides in North Carolina.

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