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WEED SCIENCE

Residual Herbicides for Palmer Amaranth Control

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ABSTRACT

Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) is a major problem in the southeastern U.S. Cooperative Extension personnel are actively promoting resistance management strategies, including integration of herbicides with other modes of action into glyphosate-based programs, to reduce selection pressure. This field experiment, conducted in five environments in North Carolina and Georgia during 2006 and 2007, evaluated residual control of Palmer amaranth by herbicides registered for use in cotton (*Gossypium hirsutum* L.). Treatments consisted of a factorial arrangement of 13 residual herbicides at 1X rates (manufacturer's suggested use rates) and 1.5X rates. All herbicides were applied preemergence (PRE) to the weeds to evaluate residual effectiveness. Results varied by environment, depending primarily upon time and amount of rainfall. Herbicides at 1.5X rates were an average of 9% more effective 20 d after application compared with 1X rates. Of the herbicides typically applied PRE or preplant, fomesafen, flumioxazin, and pyrithiobac were the most effective. These herbicides controlled Palmer amaranth 74 to 100%, depending upon environment, at 20 d. Fluometuron and diuron were intermediately effective, controlling Palmer amaranth 41 to 91%, and pendimethalin and prometryn were least effective (30 to 82%). Pyrithiobac and *S*-metolachlor were the most effective of herbicides that could be applied postemergence (POST) to cotton. Pyrithiobac (75 to 97% at 20 d) was more effective than trifloxysulfuron (34 to 88%), and *S*-metolachlor (57 to 96%) was more effective than metolachlor (32 to 86%). Flumioxazin (82 to 100% at 20 d) was the most effective option for postemergence-directed (POST-DIR) application. Diuron, linuron, linuron plus diuron, and prometryn plus trifloxysulfuron were intermediately effective (48 to 97%), and prometryn was least effective (30 to 79%). Integration of effective residual herbicides into glyphosate-based management systems will help sustain cotton production in areas infested with Palmer amaranth.

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Palmer amaranth (*Amaranthus palmeri* S. Wats.) is one of the most troublesome weeds for cotton producers in the southeastern U.S. (Webster, 2005). This weed grows rapidly and can reach 2 m or more in height (Horak and Loughin, 2000). It has an extremely high photosynthetic capacity and utilizes the C_4 photosynthetic pathway (Ehleringer, 1983). Along with rapid growth, Palmer amaranth has effective drought tolerance mechanisms that allow it to survive and grow during dry conditions (Ehleringer, 1983; Place et al., 2008; Wright et al., 1999), and it readily adapts to shading (Jha et al., 2008), which allows the plant to compete under light-limited environments such as dense crop canopies. These characteristics allow Palmer amaranth to establish a competitive dominance for light and space with crops (Monks and Oliver, 1988). A single Palmer amaranth per 9.1 m of row in cotton in Texas, 3 plants per m of row in soybean [*Glycine max* (L.) Merr.] in Arkansas, and 0.5 plant per m of row in corn (*Zea mays* L.) in Kansas reduced yield 13, 17, and 11% respectively (Klingaman and Oliver, 1994; Massinga et al., 2001; Morgan et al., 2001). In Georgia, two Palmer amaranth plants spaced every 7 m of row reduced cotton yield 23% (MacRae et al., 2007). Losses as great as 78% in soybean with Palmer amaranth densities of eight plants per m of row, 54% in cotton with densities of 10 plants per 9.1 m of row, and 91% in corn with densities of eight plants per m of row have been documented (Bensch et al., 2003; Massinga et al., 2001; Morgan et al., 2001).

In addition to its competitive advantage, Palmer amaranth can interfere with mechanical harvesting of cotton and reduce harvesting efficiency (Smith et al., 2000). Morgan et al. (2001) suggested that mechanical harvesting of cotton with Palmer amaranth at densities greater than six plants per 9.1 m of row was impractical because of the potential for damage to equipment. In uncontrolled populations, harvesting of cotton is impossible (Gardner et al., 2006).

Once established in fields, Palmer amaranth can be difficult to control due to its rapid growth, competitive ability, and prolific seed production (Bensch et al., 2003; Horak and Loughin, 2000; Keely et al., 1987; MacRae et al., 2008; Menges, 1987; Sellers et al., 2003). Continued emergence throughout the season, coupled with prolific seed production, allows Palmer amaranth to replenish seed banks quickly if control is not season long (Keely et al., 1987; Sellers et al., 2003). Glyphosate typically is efficacious on Palmer amaranth (Bond et al., 2006; Corbett et al., 2004; Norsworthy and Grey, 2004), but multiple applications are often needed for season-long control (Culpepper and York, 1998, 1999; Everitt et al., 2003; Grichar et al., 2004; Scott et al., 2002).

Cotton was planted on 600,000 ha in North Carolina, South Carolina, and Georgia in 2008 (USDA-NASS, 2009). Greater than 99% of that cotton was a glyphosate-resistant cultivar (USDA-AMS, 2008), and this cotton routinely receives multiple applications of glyphosate. Management programs consisting of only glyphosate have effectively controlled Palmer amaranth and other weeds in cotton (Culpepper and York, 1999; Culpepper et al., 2000; Scott et al., 2002). However, extensive reliance on glyphosate has led to selection for glyphosate-resistant biotypes of weeds (Heap, 2009). Glyphosate-resistant Palmer amaranth was first suspected in Georgia in 2004 and confirmed in 2005 (Culpepper et al., 2006), and it was first noted in North Carolina in 2005 (York et al., 2007). Currently, an estimated 120,000 ha in Georgia and 75,000 ha in North Carolina are thought to be infested with the resistant biotype (Culpepper et al., 2008). Glyphosate-resistant Palmer amaranth also occurs in Arkansas, South Carolina, and Tennessee (Heap, 2009; Norsworthy et al., 2008; Steckel et al., 2008; York et al., 2007).

Failure to adopt a strategy that effectively controls glyphosate-resistant Palmer amaranth can result in total crop failure (Whitaker, 2009). A key component of an effective management strategy will be integration of herbicides with different modes of action and residual activity. Herbicides applied preemergence (PRE) reduce early season weed interference and often improve season-long control of Palmer amaranth (Culpepper and York, 1998; Keeling et al., 2006; Reddy, 2001; Toler et al., 2002; Whitaker et al., 2008). Herbicides such as diuron, fluometuron, fomesafen, pendimethalin, prometryn, and pyrithiobac can be applied PRE to cotton for residual control of Palmer amaranth and other weeds; flumioxazin can be used as an early preplant surface-applied treatment (York and Culpepper, 2009). Pyrithiobac and trifloxysulfuron applied postemergence (POST) control Palmer amaranth of small size (Corbett et al., 2004; Dotray et al., 1996; Porterfield et al., 2003), although the manufacturer of trifloxysulfuron does not claim control and the manufacturer of pyrithiobac claims only suppression of this weed (Anonymous, 2009a; 2009b). Both trifloxysulfuron and pyrithiobac can be applied with glyphosate to provide residual control of Palmer amaranth (Branson et al., 2005; Burke and Wilcut, 2004; Grichar and Minton, 2007). Metolachlor and *S*-metolachlor may be mixed with glyphosate and applied POST to cotton (York and Culpepper, 2009). These herbicides do not have POST activity on Palmer amaranth, but the residual activity of metolachlor and *S*-metolachlor has been documented to increase effectiveness of glyphosate applied POST to Palmer amaranth in cotton (Clewis et al., 2006).

Several herbicides can be applied to cotton as postemergence-directed (POST-DIR) sprays when a height difference exists between cotton and weeds (Wilcut et al., 1997; York and Culpepper, 2009). These herbicides not only control small, newly emerged weeds but also provide residual control (Askew et al., 2002; Porterfield et al., 2003; Price et al., 2008). Residual herbicides are being actively promoted to aid in management of glyphosate-resistant Palmer amaranth and to delay further evolution of resistance (York and Culpepper, 2009; Steckel, 2008; Stephenson et al., 2008). This research was conducted to evaluate residual control of Palmer amaranth by various herbicides available to cotton producers. Information of this nature will be essential in developing sustainable management systems for glyphosate-resistant cotton in the southeastern U.S.

MATERIALS AND METHODS

The experiment was conducted at sites near Oglethorpe, GA and Mount Olive, NC during 2006 and 2007 and near Parkton, NC during 2006. Each site was selected based on heavy infestations of Palmer amaranth in which portions of the populations were glyphosate-resistant. Soils information and Palmer amaranth densities are provided in Table 1. These soils are typical of those where glyphosate-resistant Palmer amaranth has been most problematic in North Carolina and Georgia.

The experimental design was a randomized complete block with treatments replicated three or four times, depending upon location. Plots consisted of four 96-cm rows 9 m long. Cotton was planted in a conventional tillage system and herbicides were applied on the same day; application dates are shown in Table 1. Treatments consisted of a factorial arrangement of 13 herbicides applied at the manufacturer's suggested application rates for the soil type (1X rate) and at a 1.5X rate. Residual herbicides and their respective 1X rates included diuron (Direx 4L; Dupont Crop Protection Co., Inc., Wilmington, DE) at 1120 g a.i. ha^{-1}; flumioxazin (Valor SX; Valent U.S.A. Corp., Walnut Creek, CA) at 54 g a.i. ha^{-1}; fluometuron (Cotoran 4L; Griffin LLC, Valdosta, GA) at 1120 g a.i. ha^{-1}; fomesafen (Reflex; Syngenta Crop Protection, Inc., Greensboro, NC) at 280 g a.i. ha^{-1}; linuron (Linex 4L; Dupont Crop Protection Co., Inc.) at 1120 g a.i. ha^{-1}; linuron plus diuron (Layby Pro; Dupont Crop Protection Co., Inc.) at 560 + 560 g a.i. ha^{-1}; metolachlor (Stalwart; Sipcam Agro USA, Inc., Roswell, GA) at 1120 g a.i. ha^{-1}; pendimethalin (Prowl H_2O; BASF Ag Products, Research Triangle Park, NC) at 1064 g a.i. ha^{-1}; prometryn (Caparol 4L; Syngenta Crop Protection, Inc.) at 1120 g a.i. ha^{-1}; prometryn plus trifloxysulfuron (Suprend; Syngenta Crop Protection, Inc.) at 888 + 8 g a.i. ha^{-1}; pyrithiobac (Staple LX; Dupont Crop Protection Co., Inc.) at 48 g a.i. ha^{-1}; *S*-metolachlor (Dual Magnum; Syngenta Crop Protection, Inc.) at 1067 g a.i. ha^{-1}; and trifloxysulfuron (Envoke; Syngenta Crop Protection, Inc.) at 5.3 g ha^{-1}. A non-treated check was also included. Some of the herbicides evaluated are not intended for PRE application on cotton, but the objective of this study was to determine residual control obtained from each herbicide. Therefore, all herbicides were applied PRE regardless of intended application timing. Herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TeeJet XR 11002 nozzles; Spraying Systems Co., Wheaton, IL) calibrated to deliver 140 L ha^{-1} at 160 kPa.

Weed control was visually estimated 20, 40, and 60 d after application using a scale of 0 to 100, where 0 = no weed control and 100 = complete weed control (Frans et al., 1986). In Oglethorpe during 2007, no rainfall occurred until 18 d after application. Although only a few weeds emerged during this dry period, the weeds that did emerge were not controlled by any herbicide due to lack of herbicide activation. Immediately after the initial rainfall, potassium salt of glyphosate (Roundup WeatherMAX; Monsanto Co., St. Louis, MO) was applied at 1.2 kg ae ha^{-1} over the entire trial area and visual ratings were recorded at 20-d intervals thereafter. The initial flush of Palmer amaranth, fewer than 3 plants per m^2, was not considered in visual ratings. Cotton response to the herbicides was not evaluated as this was not the objective of the experiment and because a number of the herbicides are not intended for PRE application. Data were subjected to analyses of variance with partitioning appropriate for the factorial treatment arrangement. Data were arcsine square root transformed before analysis (Ahrens et al., 1990). Analyses were performed with the PROC MIXED procedure of SAS (version 9.1; SAS Institute Inc., Cary, NC). Each

Table 1. Description of soils, herbicide application dates, and Palmer amaranth densities at experiment sites.

Year	Site	Application date	Soil series[z]	Soil pH (units)	Soil humic or organic matter (%)	Palmer amaranth density (no. m^{-2})
2006	Mt. Olive, NC	5 May	Wagram[w]	6.3	0.51[w]	300
2006	Oglethorpe, GA	1 May	Dothan[x]	6.3	2.00[v]	195
2006	Parkton, NC	24 May	Wagram	6.0	0.56[w]	180
2007	Mt. Olive, NC	14 May	Wagram	5.5	0.60[w]	150
2007	Oglethorpe, GA	1 May	Dothan	6.3	2.00[v]	70

[z] Texture of all soils is loamy sand.

[y] Loamy, kaolinitic, thermic Arenic Kandiudults

[x] Fine-loamy, siliceous, thermic Plinthic Paleudults

[w] Soil humic matter was determined as described by Mehlich (1984).

[v] Soil organic matter was determined according to a modification of the method of Walkley and Black (1934).

year and location was considered an environment (McIntosh, 1983), and environments were treated as fixed experimental effects whereas replications were treated as random experimental effects. Data were averaged over environments, herbicides, and herbicide rates as appropriate and means of significant main effects and interactions were separated with Fisher's Protected LSD Test at $P \leq 0.05$. Non-transformed means are reported with interpretation based on transformed data.

RESULTS AND DISCUSSION

Data from each environment were analyzed separately due to treatment by environment interactions. The herbicide by rate interaction was not significant except for the 60-d evaluation at Oglethorpe in 2006 and Mount Olive in 2007. The main effect of application rates was significant at most evaluation periods and environments, and the main effect of herbicides was significant at all evaluations and environments.

Herbicide rates affected Palmer amaranth control similarly across all environments 20 d after application. Control, averaged over herbicides, varied among environments from 53 to 89% with the 1X rate and 65 to 93% with the 1.5X rate (Table 2). Averaged over environments, herbicides applied at 1.5X rates were 9% more effective than when applied at 1X rates. Except for Oglethorpe in 2007, control decreased 10 to 59% by 40 d, and control continued to decrease between 40 and 60 d at each environment. Greater control was noted with the 1.5X rate at 40 d (5 to 15%) and 60 d (10 to 13%) after application at Oglethorpe in both years and Parkton in 2007. Herbicide rate did not affect control at 40 or 60 d in either year at Mount Olive. This was likely due to poor control regardless of the herbicides or rates applied. Control at Mount Olive was 10% or less by 40 d in 2006 and 35% or less in 2007. Control at Mount Olive in 2007 further declined to 10% or less by 60 d.

Irrigation was not available at any site, and rainfall patterns were likely a major contributor to variation in control among environments. Greatest control at 40 and 60 d was achieved at Oglethorpe in 2006 (Table 2). At this location, nearly 13 cm of rainfall occurred within the first 10 d after herbicide application to adequately activate the herbicides (Table 3). No rainfall occurred during the subsequent 20 d, and only 1.2 cm of rainfall was received during the period of 11 to 50 d after herbicide application. Dry soil conditions following the first 2 wk of the evaluation period greatly reduced further weed seed germination. Overall Palmer amaranth control was least at Mount Olive in 2006 (Table 2), where adequate rainfall was received throughout the evaluation period. These rainfalls lead to continued Palmer amaranth germination throughout the evaluation period.

Table 2. Palmer amaranth control as affected by herbicide rate 20, 40, and 60 d after herbicide application.

Residual herbicide rate[y]	Palmer amaranth control (%)[z]					
	2006			2007		Pooled across Environments[x]
	Oglethorpe	Mount Olive	Parkton	Oglethorpe	Mount Olive	
	20 d after application					
1 X	89	53	77	54	82	71
1.5 X	93*	67*	87*	65*	86*	80*
	40 d after application					
1 X	69	10	62	59	30	--
1.5 X	80*	8	77*	64*	35	--
	60 d after application					
1 X	52	0	17	39	8	--
1.5 X	64*	0	30*	49*	10	--

[z] Data averaged over 13 herbicides. Means for the 1.5X rate within an evaluation period followed by an asterisk are different from the means of the 1X rate at $P \leq 0.05$.

[y] 1X rate is the manufacturer's suggested use rate for the soil type.

[x] Data pooled across environments due to lack of rate by environment interaction.

Table 3. Rainfall at experiment sites.

Interval after herbicide application (d)	Rainfall (cm)				
	Oglethorpe 2006	Mount Olive 2006	Parkton 2006	Oglethorpe 2007	Mount Olive 2007
0 to 5	0.0	2.24	0.15	0.0	0.97
6 to 10	12.7	1.22	0.03	0.0	0.00
11 to 15	0.0	0.00	3.81	0.0	0.00
16 to 20	0.0	1.70	4.26	1.2	4.22
21 to 25	0.0	0.79	7.49	0.0	0.00
26 to 30	0.0	2.54	5.72	0.0	0.03
31 to 40	0.8	6.76	3.53	6.3	1.55
41 to 50	0.4	6.02	3.40	3.5	1.47
51 to 60	2.8	3.74	1.37	0.2	3.02

In this study, all herbicides were applied PRE to better observe residual activity; however, not all of the herbicides are intended to be applied in this manner to cotton. Herbicides in this study that are typically applied PRE include diuron, fluometuron, fomesafen, pendimethalin, prometryn, and pyrithiobac (York and Culpepper, 2009). Flumioxazin is applied 14 to 30 d ahead of planting, depending upon rate and tillage system (Anonymous, 2009c).

Although some differences occurred among environments, flumioxazin, fomesafen, and pyrithiobac were generally the most effective of the herbicides typically applied preplant or PRE. Flumioxazin, fomesafen, and pyrithiobac were similarly effective 20 d after treatment at Oglethorpe in 2006, controlling Palmer amaranth 97 to 100% (Table 4). Control by pyrithiobac declined to 87% by 40 and 69 to 78% by 60 d; flumioxazin and fomesafen still controlled Palmer amaranth 99% at 40 d and 95 to 98% at 60 d (Tables 5 and 6). Pyrithiobac was the most effective herbicide 20 d after treatment in both years at Mount Olive, controlling Palmer amaranth 93 to 97% (Table 4). Flumioxazin and fomesafen were the next most effective herbicides, controlling Palmer amaranth 74 to 83% in 2006 and 89 to 93% in 2007 at 20 d. Control by all herbicides declined rapidly after 20 d at Mount Olive in both years. Control by flumioxazin, fomesafen, and pyrithiobac at Mount Olive declined to 18 to 27% at 40 d in 2006 and 42 to 69% at 40 d in 2007 (Table 5). Flumioxazin and fomesafen controlled Palmer amaranth 23% or less at 60 d in both years at Mount Olive (Table 6). Pyrithiobac controlled Palmer amaranth only 1% at 60 d at Mount Olive in 2006. At this location in 2007, pyrithiobac at 1X and 1.5X rates controlled the weed 14 and 53%, respectively, at 60 d. Flumioxazin was most effective at Parkton, where it controlled Palmer amaranth 96, 90, and 57% at 20, 40, and 60 d after treatment, respectively (Tables 4, 5, and 6). Fomesafen and pyrithiobac were similarly effective at Parkton, controlling Palmer amaranth 87 to 88% at 20 d, 77% at 40 d, and 27 to 28% at 60 d. Flumioxazin, fomesafen, and pyrithiobac were similarly effective (75 to 82% control) 20 d after treatment at Oglethorpe in 2007. By 40 d, flumioxazin controlled the weed 85% compared with 73% by fomesafen and pyrithiobac. At 60 d, flumioxazin, fomesafen, and pyrithiobac were also similarly effective (68 to 81% control).

Diuron and fluometuron were generally intermediately effective among the preplant and PRE herbicides whereas pendimethalin and prometryn tended to be least effective. At Parkton in 2006 and Oglethorpe in 2007, control by diuron and fluometuron was similar at 20 and 40 d (Tables 4 and 5). At each of these locations, control by diuron and fluometuron usually exceeded control by pendimethalin and prometryn at 20 and 40 d. By 60 d at Oglethorpe in 2007, control by diuron, fluometuron, and pendimethalin was similar and greater than control by prometryn (Table 6). At Parkton, control by all of these herbicides declined to 24% or less by 60 d. At Oglethorpe in 2006, Palmer amaranth control at 20 and 40 d was similar with fluometuron, pendimethalin, and prometryn but less than control by diuron (Tables 4 and 5). A herbicide-by-herbicide rate interaction was noted at 60 d at Oglethorpe in 2006 (Table 6). Diuron was more effective than fluometuron, pendimethalin, or prometryn at the 1X rates, but diuron and pendimethalin were similarly effective when applied at 1.5X rates and more effective than fluometuron. At Mount Olive in 2006, fluometuron, pendimethalin, and prometryn were similarly effective at 20 d but less effective than diuron (Table 4). Control by all of these herbicides declined to 4% or less by 40 d (Table 5). Control by diuron, fluometuron, pendimethalin, and prometryn was generally similar at 20 and 40 d at Mount Olive in 2007. Control by these herbicides declined to 3% or less by 60 d (Table 6).

Table 4. Palmer amaranth control 20 d after herbicide application.

Residual herbicides[y]	Control (%)[z]				
	2006			2007	
	Oglethorpe	Mt. Olive	Parkton	Oglethorpe	Mt. Olive
Diuron	91 de	71 c	81 cde	55 de	86 cde
Flumioxazin	100 a	83 b	96 a	82 a	93 b
Fluometuron	86 fg	49 ef	83 cde	61 bcd	79 ef
Fomesafen	99 ab	74 bc	87 bcd	78 a	89 bc
Linuron	92 cd	58 de	73 fg	81 a	87 cd
Linuron + diuron	91cd	68 cd	81 de	71 abc	85 cde
Metolachlor	86 ef	32 g	79 ef	36 fg	68 g
Pendimethalin	82 fg	49 ef	61 h	44 ef	73 fg
Prometryn	79 g	39 fg	70 g	30 g	79 ef
Prometryn + trifloxysulfuron	97 ab	75 bc	95 a	48 def	93 b
Pyrithiobac	97 ab	93 a	88 bc	75 ab	97 a
S-metolachlor	96 bc	57 de	90 b	57 de	81 de
Trifloxysulfuron	88 def	34 g	86 cde	57 cde	79 ef

[z] Data averaged over 1X and 1.5X the manufacturer's suggested use rate for each residual herbicide. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[y] Residual herbicides and their respective 1X rates (manufacturer's suggested use rates) are : diuron (1120 g ha^{-1}); flumioxazin (54 g ha^{-1}); fluometuron (1120 g ha^{-1}); fomesafen (280 g ha^{-1}); linuron (1120 g ha^{-1}); linuron + diuron (560 + 560 g ha^{-1}); metolachlor (1120 g ha^{-1}); pendimethalin (1064 g ha^{-1}); prometryn (1120 g ha^{-1}); prometryn + trifloxysulfuron (888 + 8 g ha^{-1}); pyrithiobac (48 g ha^{-1}); *S*-metolachlor (1067 g ha^{-1}); and trifloxysulfuron (5.3 g ha^{-1}).

Table 5. Palmer amaranth control 40 d after herbicide application.

Residual herbicides[y]	Control (%)[z]				
	2006			2007	
	Oglethorpe	Mt. Olive	Parkton	Oglethorpe	Mt. Olive
Diuron	76 cd	4 def	72 bcd	64 cde	15 gh
Flumioxazin	99 a	18 abc	90 a	85 a	42 cd
Fluometuron	65 e	0 f	69 b-e	61 de	24 efg
Fomesafen	99 a	19 ab	77 b	73 bc	61 ab
Linuron	62 e	4 c-f	61 ef	80 ab	25 efg
Linuron + diuron	69 de	4 def	65 cde	73 bc	19 fg
Metolachlor	60 e	6 c-f	63 def	42 g	20 fg
Pendimethalin	64 e	0 f	44 g	46 fg	6 h
Prometryn	57 e	4 e	51 fg	27 h	18 gh
Prometryn + trifloxysulfuron	80 cd	13 a-d	87 a	58 ef	53 bc
Pyrithiobac	87 bc	27 a	77 b	73 bcd	69 a
S-metolachlor	86 b	4 def	76 bc	60 e	32 def
Trifloxysulfuron	64 e	11 b-e	73 bcd	58 ef	37 cde

[z] Data averaged over 1X and 1.5Xthe manufacturer's suggested use rate for each residual herbicide. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[w] Residual herbicides and their respective 1X rates (manufacturer's suggested use rates) are: diuron (1120 g ha^{-1}); flumioxazin (54 g ha^{-1}); fluometuron (1120 g ha^{-1}); fomesafen (280 g ha^{-1}); linuron (1120 g ha^{-1}); linuron + diuron (560 + 560 g ha^{-1}); metolachlor (1120 g ha^{-1}); pendimethalin (1064 g ha^{-1}); prometryn (1120 g ha^{-1}); prometryn + trifloxysulfuron (888 + 8 g ha^{-1}); pyrithiobac (48 g ha^{-1}); *S*-metolachlor (1067 g ha^{-1}); and trifloxysulfuron (5.3 g ha^{-1}).

Table 6. Palmer amaranth control 60 d after herbicide application.

Residual herbicides[y]	Control (%)[z]						
	2006				2007		
	Oglethorpe		Mt. Olive[x]	Parkton[x]	Oglethorpe[x]	Mt. Olive	
	1 X	1.5 X				1 X	1.5 X
Diuron	**53 g-j**	**72 cde**	**1 a**	**19 c-f**	**55 bc**	**0 g**	**1 fg**
Flumioxazin	**95 ab**	**97 a**	**1 a**	**57 a**	**81 a**	**8 def**	**14 b-e**
Fluometuron	**33 mno**	**44 i-m**	**1 a**	**24 cde**	**46 c**	**0 g**	**3 efg**
Fomesafen	**95 ab**	**98 a**	**2 a**	**28 c**	**73 ab**	**23 bc**	**22 b**
Linuron	**38 k-n**	**47 h-l**	**0 a**	**16 def**	**38 cd**	**4 efg**	**1 fg**
Linuron + diuron	**50 hij**	**56 ghi**	**0 a**	**11 f**	**39 cd**	**0 g**	**9 efg**
Metolachlor	**25 o**	**48 h-k**	**0 a**	**14 ef**	**28 de**	**3 efg**	**10 c-f**
Pendimethalin	**26 no**	**62 efg**	**0 a**	**12 f**	**41 cd**	**0 g**	**0 g**
Prometryn	**35 l-o**	**29 no**	**0 a**	**10 f**	**8 f**	**1 fg**	**0 g**
Prometryn + trifloxysulfuron	**64 d-g**	**75 cd**	**0 a**	**41 ab**	**30 de**	**15 bcd**	**16 bcd**
Pyrithiobac	**69 c-f**	**78 c**	**1 a**	**27 bc**	**68 ab**	**14 bcd**	**53 a**
***S*-metolachlor**	**58 fgh**	**90 b**	**0 a**	**24 cd**	**46 c**	**11 b-e**	**10 b-e**
Trifloxysulfuron	**38 k-n**	**41 j-m**	**1 a**	**23 cde**	**19 e**	**3 fg**	**10 b-e**

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

[y] Residual herbicides and their respective 1X rates (manufacturer's suggested use rates) are: diuron (1120 g ha^{-1}); flumioxazin (54 g ha^{-1}); fluometuron (1120 g ha^{-1}); fomesafen (280 g ha^{-1}); linuron (1120 g ha^{-1}); linuron + diuron (560 + 560 g ha^{-1}); metolachlor (1120 g ha^{-1}); pendimethalin (1064 g ha^{-1}); prometryn (1120 g ha^{-1}); prometryn + trifloxysulfuron (888 + 8 g ha^{-1}); pyrithiobac (48 g ha^{-1}); *S*-metolachlor (1067 g ha^{-1}); and trifloxysulfuron (5.3 g ha^{-1}).

[x] Data averaged over 1X and 1.5X the manufacturer's suggested rate for each residual herbicide.

Metolachlor, *S*-metolachlor, pyrithiobac, and trifloxysulfuron can be applied POST to cotton (York and Culpepper, 2009). Pyrithiobac and trifloxysulfuron exhibit both PRE and POST activity on weeds when applied POST. Although metolachlor and *S*-metolachlor have little to no POST activity on emerged weeds, the residual activity from these herbicides applied POST can be beneficial in management programs for Palmer amaranth (Clewis et al., 2006).

Greater control of Palmer amaranth at all evaluation dates was observed with *S*-metolachlor than with metolachlor at Parkton and at Oglethorpe in both years (Tables 4, 5, and 6). Greater control by *S*-metolachlor also was noted in both years at Mount Olive at 20 d. At both Mount Olive locations, however, control declined greatly by 40 d, and no differences were noted between metolachlor and *S*-metolachlor. *S*-metolachlor controlled Palmer amaranth 90 to 96% at 20 d and 76 to 86% at 40 d at Parkton and Oglethorpe in 2006. Control at Parkton declined to 24% by 60 d and at Oglethorpe to 58% with the 1X rate. Control by the 1.5X rate remained at 90% at 60 d at Oglethorpe. Control was less at Oglethorpe in 2007, but the control remained relatively constant over time. At this location, *S*-metolachlor controlled Palmer amaranth 57, 60, and 46% at 20, 40, and 60 d, respectively. Metolachlor has four stereoisomers. Previous research has shown that on a gram-for-gram basis, products containing metolachlor (equal mixture of *R* and *S* isomer pairs) are about 65% as effective on weeds as products containing predominately *S*-metolachlor (O'Connell et al., 1998). However, when application rates are adjusted to account for this difference in activity, metolachlor and *S*-metolachlor are equally effective (Shaner et al., 2006). In our study, control by metolachlor at the 1.5X rate was similar to control by *S*-metolachlor at the 1X rate (data not shown).

Pyrithiobac and trifloxysulfuron were similarly effective at Parkton. These two herbicides controlled Palmer amaranth 86 to 88%, 73 to 77%, and 23 to 26% at 20, 40, and 60 d, respectively (Tables 4, 5, and 6). In the other four environments, however, pyrithiobac was more effective than trifloxysulfuron. At Oglethorpe in 2006 and at Mount Olive in 2007, pyrithiobac controlled Palmer amaranth 97% at 20 d and 69 to 87% at 40 d compared with 79 to 88% control by trifloxysulfuron at 20 d and 37 to 64% at 40 d. A herbicide-by-herbicide rate interaction was noted at both locations at 60 d, but regardless of rate, pyrithiobac was more effective than trifloxysulfuron. Pyrithiobac at a 1.5X rate controlled Palmer amaranth 53 to 78% compared with 10 to 41% control by trifloxysulfuron at 60 d. At Mount Olive in 2006, pyrithiobac controlled Palmer amaranth 93% at 20 d compared with 34% control by trifloxysulfuron. Control had declined greatly by 40 d, but pyrithiobac was still the more effective herbicide. Pyrithiobac was less effective at 20 d at Oglethorpe in 2007 compared with the other locations. However, control by pyrithiobac remained relatively constant over time at this location. Regardless of the evaluation date, pyrithiobac was more effective than trifloxysulfuron at this location. The 1X rate of pyrithiobac chosen for this study was primarily the manufacturer's recommended rate for PRE applications. Pyrithiobac can be applied POST at rates approximately twice the 1X rate in this study (Anonymous, 2009b), and one would anticipate a greater difference in control between pyrithiobac and trifloxysulfuron if pyrithiobac had been applied at normal POST application rates. Palmer amaranth was more effectively controlled by pyrithiobac than *S*-metolachlor at 20 and 40 d at Oglethorpe in 2007 and Mount Olive in both years (Tables 4 and 5). The same observation was made at 60 d at Oglethorpe in 2007 and with the 1.5X rates at Mount Olive in 2007 (Table 6). Neither herbicide controlled Palmer amaranth at 60 d at Mount Olive in 2006. Pyrithiobac and *S*-metolachlor were similarly effective at 20 and 40 d at Oglethorpe in 2006 and at Parkton. At 60 d, both herbicides were similarly effective at Parkton and with 1X rates at Oglethorpe in 2006, but *S*-metolachlor at the 1.5X rate was more effective than pyrithiobac at 60 d at Oglethorpe in 2006. Pyrithiobac was more effective than metolachlor at all environments and evaluation dates except the 60-d evaluation at Mount Olive in 2006 where no control was noted with either herbicide.

Every herbicide evaluated in this study can be applied as a POST-DIR spray in cotton. However, only diuron, flumioxazin, linuron, linuron plus diuron, prometryn, and prometryn plus trifloxysulfuron are typically applied in this manner in North Carolina and Georgia. As POST-DIR sprays to cotton, these herbicides are usually mixed with either MSMA or glyphosate (York and Culpepper, 2009). These combinations control emerged weeds, and the diuron, flumioxazin, linuron, linuron plus diuron, prometryn, and prometryn plus trifloxysulfuron in the mixtures can provide additional residual control. In this study, all herbicides were applied PRE to the weeds, so only the residual effects of these POST-DIR herbicides were evaluated.

Flumioxazin was among the most effective herbicides at each evaluation at each environment although prometryn plus trifloxysulfuron and flumioxazin were similarly effective at four of the five environments at 20 d and three of the five environments at 40 and 60 d (Tables 4, 5, and 6). Diuron and diuron plus linuron were similarly effective in most cases, but linuron was often less effective than diuron. In many cases, prometryn was the least effective of these POST-DIR herbicides. Prometryn was always less effective than prometryn plus trifloxysulfuron or flumioxazin.

Previous research has clearly demonstrated that good residual control, beginning with preplant or PRE herbicides, is critical to manage glyphosate-resistant Palmer amaranth (Culpepper et al., 2008; Whitaker et al., 2008). The purpose of this experiment was to find the most effective residual herbicides that could be integrated into a glyphosate-based system. The most effective PRE herbicides were found to be fomesafen and pyrithiobac. Flumioxazin, which could be applied 2 to 4 wk ahead of planting, was similarly effective. In a normal production system, flumioxazin applied early preplant might be less effective, relative to fomesafen, than was observed in this study due to herbicide dissipation during the interval between application and cotton planting. However, fomesafen or other herbicides applied PRE must receive timely rainfall for activation; lack of timely activation leads to poor control (Culpepper et al., 2007; Whitaker, 2009). Early preplant applications of a herbicide such as flumioxazin would increase the chances of receiving rainfall for activation prior to cotton planting or weed emergence. One could increase the consistency of control and the overall level of control by using both a preplant and a PRE herbicide (Whitaker et al., 2008). In Georgia and North Carolina, Extension personnel are recommending a preplant residual herbicide followed by one or more herbicides applied PRE, especially for conservation tillage cotton in areas with known infestations of glyphosate-resistant palmer amaranth (Culpepper et al., 2010; York and Culpepper, 2009).

In addition to an aggressive preplant and/or PRE herbicide program, Extension personnel in Georgia and North Carolina also recommend a residual herbicide applied early POST in combination with glyphosate followed by another residual herbicide applied at lay-by (Culpepper et al., 2010; York and Culpepper, 2009). Among the residual herbicides applied POST in cotton in this study, pyrithiobac was more effective than *S*-metolachlor or trifloxysulfuron. However, widespread resistance to acetolactate synthase-inhibiting herbicides (Heap, 2009) limits the areas where pyrithiobac would be effective. Among the POST-DIR herbicides, flumioxazin and prometryn plus trifloxysulfuron were most effective.

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